AIR FORCE MATERIALS LABORATORY
RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND

CONTRACT AF 33(615)-2460
PROJECT 7381; TASK 738103

NIOBIUM ALLOYS and COMPOUNDS

DONALD L. GRIGSBY

DATA SHEET DS-148
JANUARY 28, 1966

EPIC

ELECTRONIC
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FOREWORD

The Electronic Properties Information Center (EPIC) was established in June 1961, at Hughes Aircraft Company, Culver City, California. It is operated under contract with the Air Force Materials Laboratory, Research and Technology Division, Wright-Patterson Air Force Base, Ohio. The contract was initiated under Project No. 7381, Task No. 738103, with Mr. R.F. Klinger acting as Project Engineer.

The EPIC Information Analysis Center is a center for the collection, review and analysis of the scientific and technical literature on the electrical and electronic properties of materials. Its major function is to evaluate, compile and publish the experimental data from that literature. Through the medium of a series of publications such as Data Sheets, Special Reports, State-of-the-Art Reports, Computer Bibliographies, and services including special studies, answers to technical inquiries, research support is provided to the DoD community. EPIC input is primarily from the open literature. A large number of abstract journals, in addition to about 40 other journals, and the unclassified report literature are completely searched.

This report consists of the compiled data sheets on niobium alloys and compounds. A full list of EPIC publications to date appears at the end of the report.

The author wishes to acknowledge the contribution of Mr. E. Schafer in the pre-publication review of the compilation. The supporting assistance of other members of the EPIC staff, in particular, Mrs. J. Forest, Miss Sharon Bender, Mr. W.S. Hodge, and Mrs. Meta Neuberger, is gratefully acknowledged.

ABSTRACT

These data sheets present a compilation of electronic properties for superconducting properties including transition temperature, critical field, critical current, electrical resistivity, and magnetic hysteresis. Electrical properties include conductivity, dielectric constant, Hall coefficient, mobility, and thermoelectric effects. Emission data have been broken down into the varied electron and photon emissions. Work functions, absorption, magnetic susceptibility, specific heat, Debye temperature and thermal conductivity data are also given. Each property is compiled over the widest possible range of parameters including bulk and film form, from references obtained in a thorough literature search.

This report has been reviewed and is approved for publication.

Emil Schafer

Emil Schafer
Assistant Head, Electronic Properties Information Center

John W. Atwood

John W. Atwood
Project Manager

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INTRODUCTION

The data given for niobium alloys and compounds in this publication are presented according to the period, rather than the group, of those elements added to niobium. Within the periodic nature of the organization some of the systems have been grouped together, such as niobium boride and niobium carbide. This has been done where the data on systems of neighboring elements are suitable for comparison. Most of the data are on the binary systems; however, available data on ternary niobium systems are given when available and pertinent.

The superconducting properties of these systems are of primary concern and are presented first, followed by other data available. Some systems such as niobium-tellurium do not show evidence of being superconducting at any temperature, still the semiconducting data are given for completeness.

None of the data on niobium-tin or niobium-zirconium are included in this publication. Each of these systems is being compiled separately and will be issued later.

As the data on these various systems are presented, every effort has been made to provide sample specifications where they are available. One particular method is used for niobium-metal alloys; that is where the samples are arc melted on a water cooled copper hearth and then remelted several times to obtain homogeneity. This has been referred to as the "standard" sample preparation in some of the captions.

One other method of sample preparation has been used to investigate the forming of materials with β-tungsten structure and with a high density of states. The HCl transport method started with sintered Nb_3M materials. The cold zone was kept at 800-900°C and the hot zone at 1000-1100°C. The results are given below for two niobium compounds, the other data are presented in the body of this publication.

Compound	Crystal type	Lattice constant a_o(Å)	T_c °K
Nb_3Ag	Cu_3Au	4.207	-
Nb_3Cu	"	"	<4.2

[Ref. 21843]

Compiling these data from as many sources as possible, it has often been necessary to change some parameters so that they are compatible with others. One example of this is in the method of measuring the amount of the element added to niobium. The two most common methods are weight percent and atomic percent, the conversion factors between these are taken from ASM Metals Handbook, 1948.

$$y = \frac{100x}{x + \frac{A}{B}(100-x)}, \qquad x = \frac{100y}{y + \frac{B}{A}(100-y)},$$

where x is the weight percent and y is the atomic percent. A common notation for atomic percentage is as follows:

$$Nb_{55}Ta_{45} \text{ or } Nb_{.55}Ta_{.45},$$

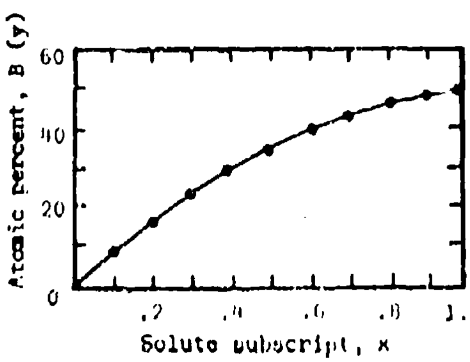
other than this, at.% or wt.% is used.

The generalized subscript x is often used to replace the numerical values; $Nb_{1-x}Ge_x$ is just another method of using atomic percent notation when x takes on specific values. However, when the notation NbC_x is used, this is not the atomic percent notation; when x = .5, i.e. $Nb_{1.0}C_{.5}$, the carbon content is in reality 33 at.%. The following nomogram aids in these conversions.

Nomogram for conversion to atomic percent B in A_1B_x:

$$x = \frac{y}{1+y}, \quad y = \frac{x}{1-x},$$

where x is the subscript for the solute, and y is the atomic percent.

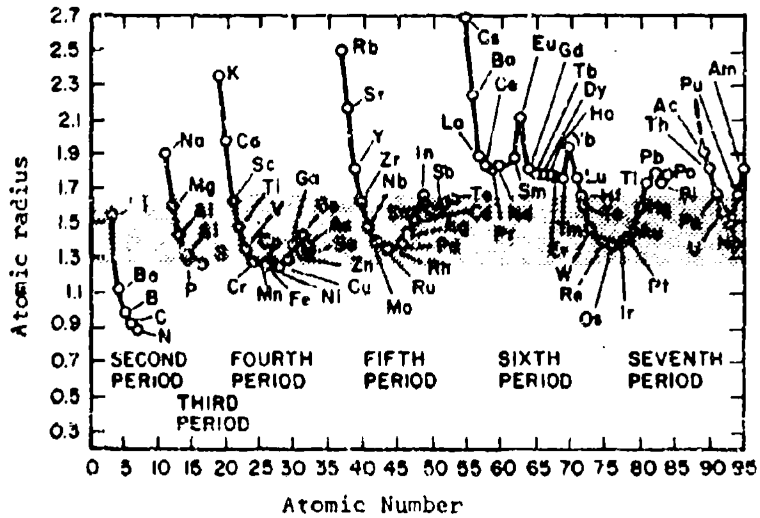


Another notation used in reporting the composition of niobium alloys and compounds is the ratio of the additional element to niobium; an example of this is C/Nb. If this is the atomic ratio, the value is easily converted to atomic percent, an atomic ratio C/Nb of .5 is 50 at.% carbon. Occasionally mole ratio C/Nb may be given when in reality atomic ratio is intended, when this is done, an attempt has been made to clarify.

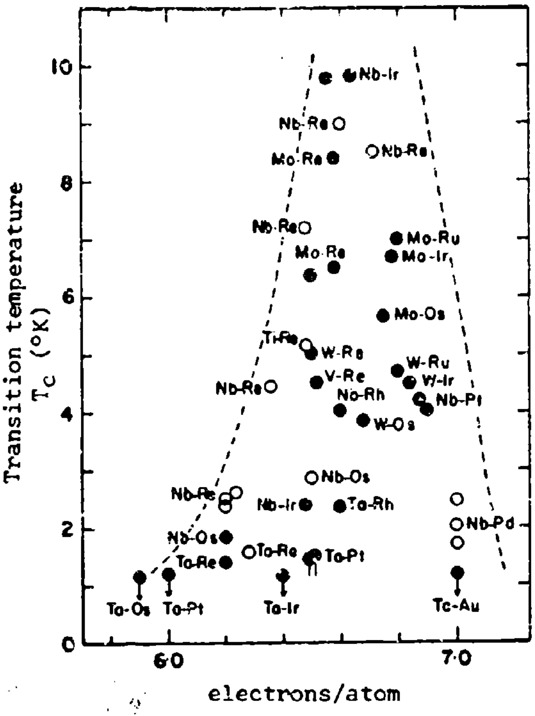
The crystalline nature of the niobium systems is of great importance in determining the properties they exhibit. This is one of the reasons why much attention has been given to phase diagrams and lattice parameters. The three main crystalline structures which show superconductivity are β-tungsten, α-manganese, and sigma. Below is a graph which shows those elements which are favorable for solid solubility in niobium.

The shaded band covers the range of radii favorable for extensive solid solubility in niobium

[Ref. 21851]



Directly correlated to the composition and crystalline structure of the niobium systems is the valence electron/atom ratio. The two following graphs show the transition temperatures as a function of this ratio for various systems in different structures.



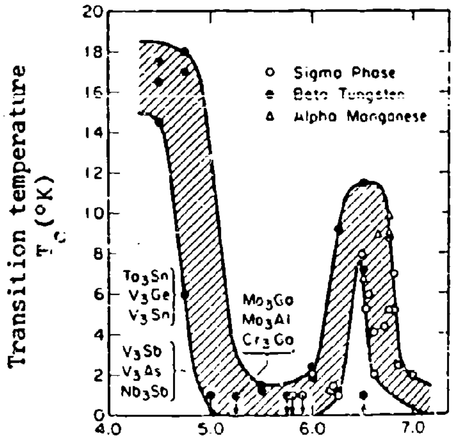
• σ structure

o α-Mn structure

[Ref. 15323]

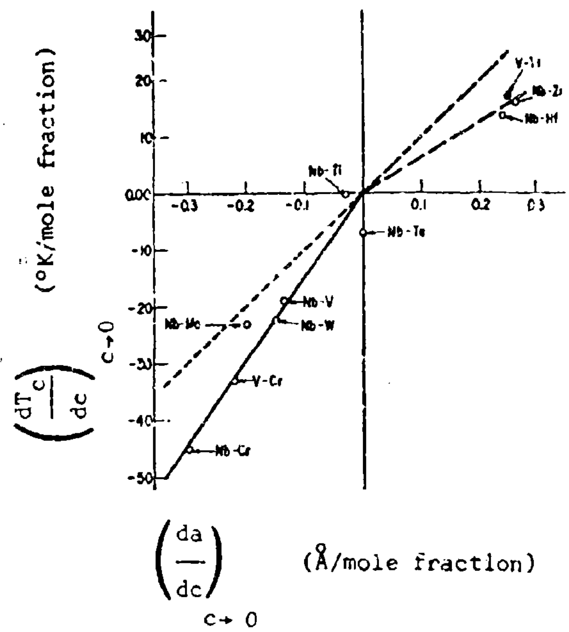
Transition temperature as
a function of e/a ratio.

Transition ;perature as
a function of e/a ratio.



[Ref. 7648]

In a 1963 paper, DeSorbo reports the effects of composition and structure on superconducting properties. The following graph shows dT_c/dc plotted against da/dc where c is the concentration and a is the lattice parameter. The size of the solute atom is one of the factors affecting the properties of the system.



The rate of change of transition temperature with composition as a function of change of lattice parameter.

[Ref. 10778]

Section 1

NIOBIUM ALLOYS AND COMPOUNDS

NIOBIUM-HYDROGEN

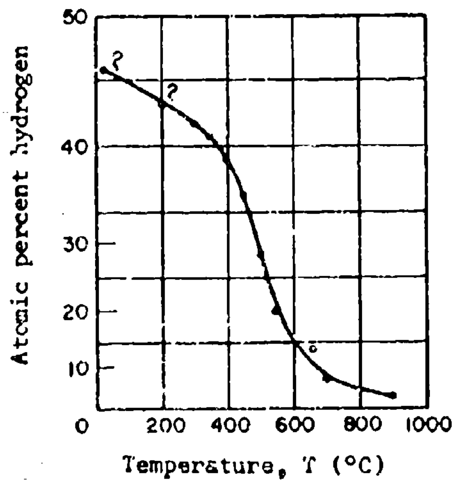
GENERAL

Niobium hydride shows a transition temperature near 9°K with low hydrogen content. This temperature value decreases as the hydrogen content is increased and has a value of about 12°K at $Nb_{1.0}H_{1.0}$.

Two distinct phases are found for the niobium-hydrogen system, an α phase up to 10 at.% hydrogen and β-niobium hydride phase above 41 at.% hydrogen. The ranges represented by these phases are given by Brauer and Herman [Ref. 20328] and Trzebiatowski and Stalinski [Ref. 20575].

Some disagreement exists over the nature of the β phase. Brauer and Herman [Ref. 20328] cite the lattice constants for an orthorhombic structure, but also interpret this phase as distended cubic. Samsonov and Anmonova [Ref. 20333] substantiate this latter symmetry in the 44 to 51 at.% hydrogen region.

Solubility isobar for hydrogen at 1 atmosphere, in niobium (98.5 wt.% pure) [Hansen Fig. 434; taken from: Sieverts, A. and H. Moritz. Z FUER ANORG. UND ALLGEM. CHEM., v. 247, 1941. p. 124.]

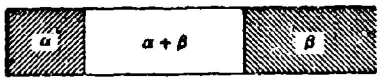


NIOBIUM-HYDROGEN

GENERAL

Mole ratio H/Nb

0	0.10	0.57	0.86†
0	0.11	0.7	0.94*



0	10.0	41.0	48.5*
0	9.1	36.4	46.0†

Phase diagram for niobium-hydrogen system. 48.5 at.% H is the maximum hydrogen content used by Brauer and Herman.

* Brauer and Herman [Ref. 20328]

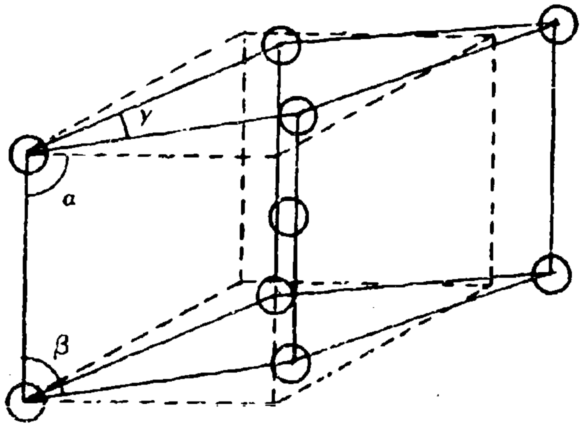
† Trzebiatowsii and Stalinski [Ref. 20575]

Pseudo cubic (orthorhombic) drawing of β-niobium hydride structure, $NbH_{.89}$.

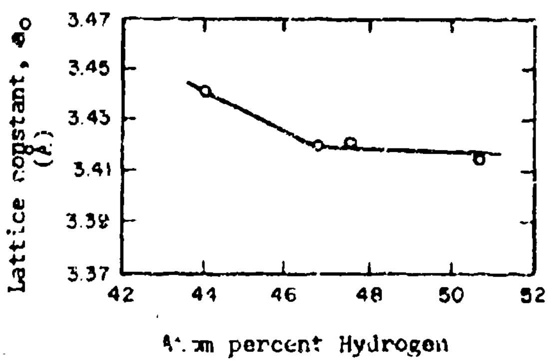
$\alpha = \beta = 90°$,

$\gamma = 89.4°$

$c_o = 3.45$



[Ref. 20328]



Lattice constant for the cubic β-NbH as a function of hydrogen content.

[Ref. 20333]

Section 1

NIOBIUM-HYDROGEN

TRANSITION TEMPERATURE

Lattice Constants and Transition Temperature

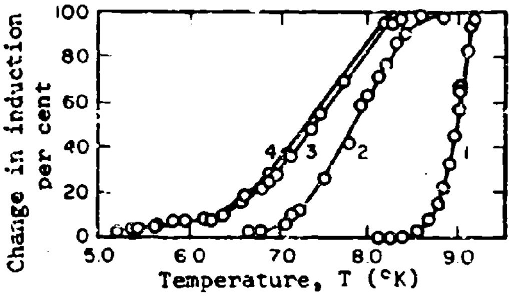
At.% H	Crystallography	Lattice constants (Å) a_o	b_o	c_o	Transition temperature (°K) Midpoint	Range	Samples	Ref.
0	bcc	3.3004*	-	-	9.98	0.90	-	9299
5.06	α-bcc	3.311±.004	-	-	7.83	2.27	Cooled from 800°C in calibrated volume of H.	"
8.5	β-bcc	3.308±.002	-	-	-	-	-	20329
8.5	α-bcc	3.427±.005	-	-	-	-	-	"
9.89	"	3.327±.003	-	-	7.38	3.25	See preceding note.	9299
17.0	"	3.312±.002	-	-	-	-	-	20329
17.0	β-bcc	3.44	-	-	-	-	-	"
32.76	α-bcc	-	-	-	7.28	3.17	See preceding note	9299
32.76	"	3.330±.003	-	-	-	-	-	20329
40.2	"	3.308±.002	-	-	-	-	-	
40.2	β-bcc	3.42	-	-	-	-	-	
47.0	"	3.45	-	-	-	-	-	
47.0	β-orthorhombic	4.84	4.90	3.45	-	-	-	20326
50.0	β-bcc	3.43	-	-	-	-	-	20333
50.0		-	-	-	12.7	-	-	20330
50.0		-	-	-	14.8	-	NbC sheath	"
67.0		4.55	-	-	-	-	-	20333

* This lattice constant taken from J. APPL. PHYS., v. 22, p. 424 (1951).

Section 1

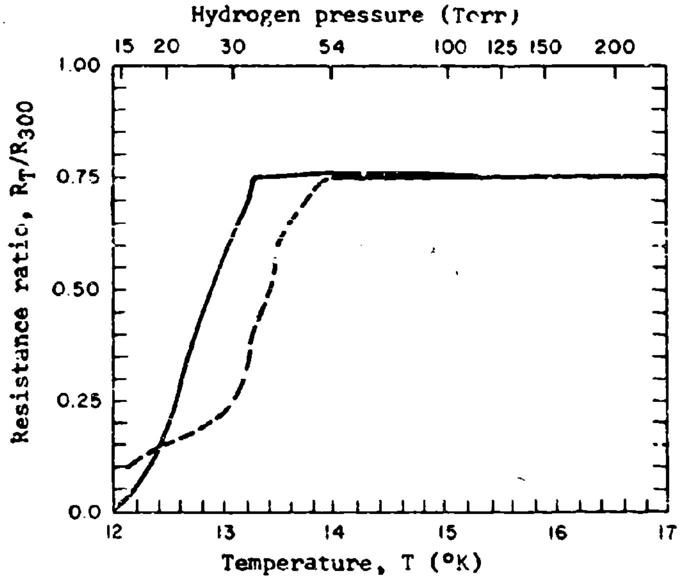
NIOBIUM-HYDROGEN

TRANSITION TEMPERATURE



Transition curves of four niobium-hydrogen systems.

1) 0 at.% H 3) 9.89 at.% H
2) 5.06 at.% H 4) 32.76 at.% H [Ref. 9299]



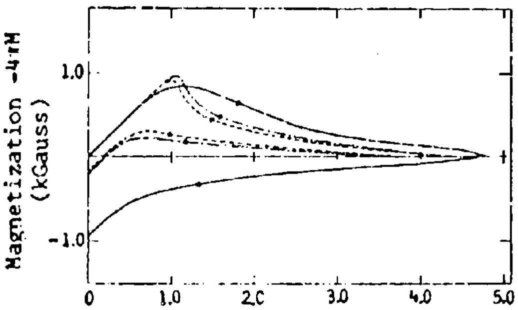
Transition curves for niobium hydride, I = 4 milliAmp, H = 0.

- - - - rising, superconducting→normal

——— falling, normal→superconducting [Ref. 20330]

Section 1
NIOBIUM-HYDROGEN

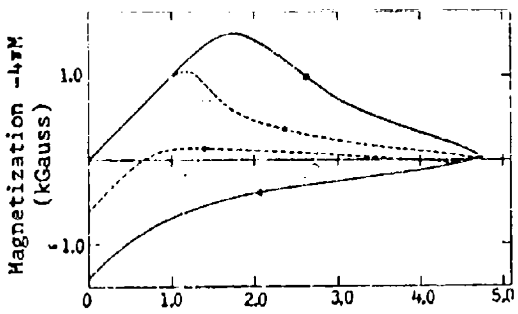
MAGNETIC HYSTERESIS



Magnetization for niobium-hydride. Data taken at 4.2°K. Sample preparation: niobium heated in 10-80 mm Hg at 800°C.

- — — — H/Nb <0.30
- - - - - H/Nb = 0.28
- ——— H/Nb = 0.45

[Ref. 21040]



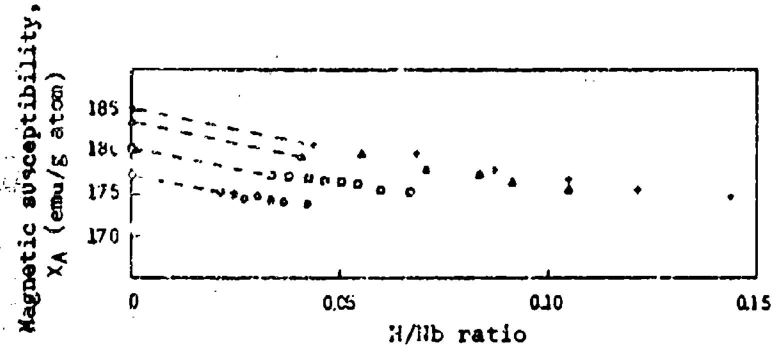
Magnetization for niobium hydride sample prepared by cathodic polarization.

- - - - - 0.16 Amp/cm, 25 hours: single crystal
- ——— 0.16 Amp/cm, 25 hours: polycrystalline

[Ref. 21040]

NIOBIUM-HYDROGEN

MAGNETIC SUSCEPTIBILITY



Atomic susceptibility of niobium-hydride as a function of hydrogen content. Samples were arc-melted under reduced argon pressure.

o	800°C
□	700
Δ	600
+	550

[Ref. 19871]

NIOBIUM HYDROGEN

SPECTRAL EMISSION

Integral intensity of $L_{\beta 2}$ bands for a niobium hydrogen compound, taking $L_{\beta 2}$ line for Nb as unity.

Compound	Intensity
NbH_x	1.06

[Ref. 16347]

Section 2

NIOBIUM ALLOYS AND COMPOUNDS

NIOBIUM-BERYLLIUM

Electrical Resistivity and Thermal Conductivity

Compound	Electrical Resistivity ($\mu\Omega$-cm)			Thermal Conductivity, K (W/cm°K)		Melting Point T_m (°C)
	25°	650°	1260°C	760°C	1480°C	
$NbBe_{12}$	55.5	166.6	200.0	0.301	0.326	1690
Nb_2Be_{17}	-	-	-	3.261	0.343	1705
Nb_2Be_{19}	-	-	-	-	-	1705

[Ref. 18169]

NIOBIUM-ZIRCONIUM-BERYLLIUM

Transition Temperature

$Nb_5Zr_2Be_8$ $T_c = 5.2°K$

[Ref. 10784]

Section 2

NIOBIUM ALLOYS AND COMPOUNDS

NIOBIUM-BORON AND NIOBIUM-CARBON SYSTEMS

GENERAL

Nb-B   Niobium combines with boron and forms three distinct compounds, NbB, Nb_3B_4, and NbB_2. Only the monoboride shows a favorable transition temperature in the 5-8°K range.

Andersson and Kiessling [Ref. 19932] have identified two phases at about 10 at.% boron which they call β and β'. The first of these seems to be stable at room temperature while the latter is stable only at higher temperatures. These authors claim a primitive cubic lattice for the β' phase with a_0 = 4.210 Å. Another phase, β'' is identified by Andersson and Kiessling between 20 and 35 at.% boron. Brewer, et al [Ref. 19752] suggest that this β'' might be a NbB_m phase containing 25 at.% boron. NbB_m was noted along with Nb and NbB after heating a 25 at.% boron sample for 8 minutes at 1650°C, but was not found in two other samples with 20 and 33 at.% boron heated for 47 minutes at 1980°C and 10 minutes at 1820°C respectively. In further experiments as the boron approached the 40 at.% level a NbB_n phase was identified by Brewer, et al, in samples prepared at 1530°C for 21 minutes and 1810°C for 9 minutes. The boron component m and n is not identifiable in either of these phases and no lattice constants are given for either of them or for Nb_3B_2.

The monoboride in the niobium-boron system shows an orthorhombic structure and is isotypic with CrB and TaB. This same orthorhombic structure carries on through to the Nb_3B_4 compound which is isotypic with Ta_3B_4. As the boron content increases, the system reaches the NbB_2 compound with a hexagonal structure of the AlB_2 (C 32) type.

Section 2

NIOBIUM-CARBON

GENERAL

Nb-C Both the "mono" and "sub" carbides of niobium have transition temperatures in the 6-10°K range, and show strong dependence on the carbon content. Near the 33 at.% carbon region ($NbC_{0.5}$) an increase in the carbon percentage by 0.60 at.% sends the transition temperature to less than 2°K. Likewise near the 50 at.% region a decrease in the carbon percentage to about 45 at.% ($NbC_{0.885}$) drops the transition temperature to less than 4°K. This dependence upon carbon content is noted even though those two compounds exhibit different crystalline structures.

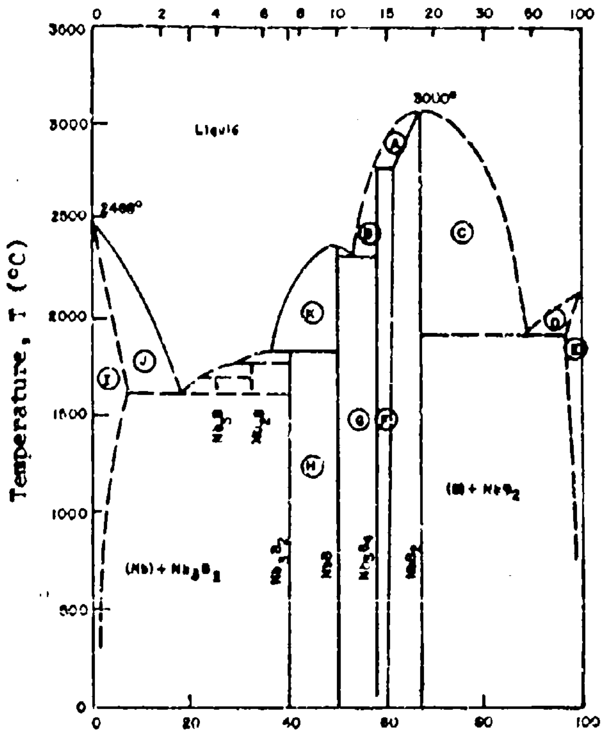
Brauer, et al* claim Nb_2C to be homogeneous between 25.9-33.3 at.% carbon and NbC to be homogeneous between 41.9-50.0 at.% carbon. The transition temperatures, however, do not reflect the homogeneity of these phases.

* Brauer, G., H. Renner, and J. Wernet. Carbides of Niobium. Z. FUER ANORG. UND ALLGEM. CHEM., v. 277, 1954. p. 249-257.

Section 2

NIOBIUM-BORON

GENERAL



A) L+NbB_2
B) L+Nb_3B_4
C) L+Nb_2
D) (B)+L
E) (B)
F) NbB_2+Nb_3B_4
G) NbB+Nb_3B_4
H) NbB+Nb_3B_2
I) (NB)
J) (NB)+L
K) L+NbB

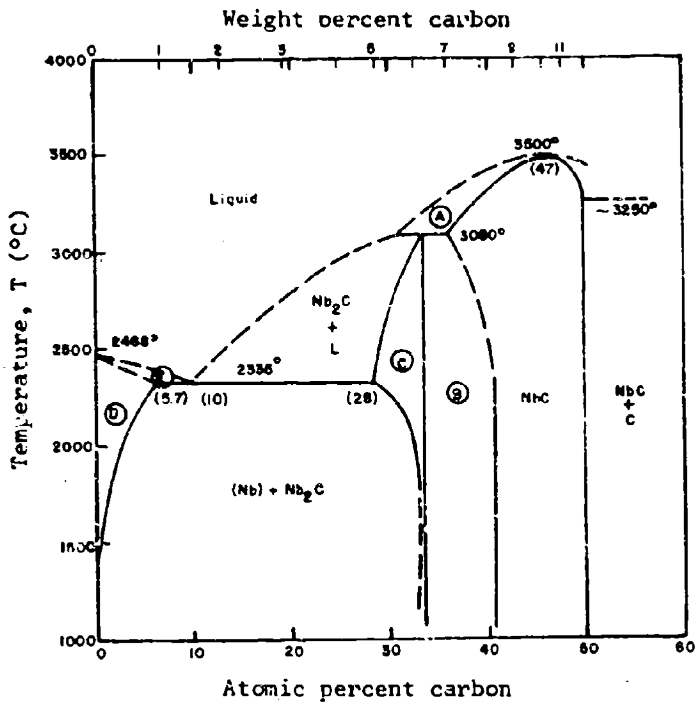
Phase diagram for niobium-boron system. [Ref. 19929]*

* W.F. SHEELY. Alloying Behavior. In COLUMBIUM AND TANTALUM. Ed. by: FRANK T. SISCO and EDWARD EPREMIAN, New York, Wiley, 1963. p. 444. Sheely has added to the Kiefer and Benovsky phase diagram.

Section 2

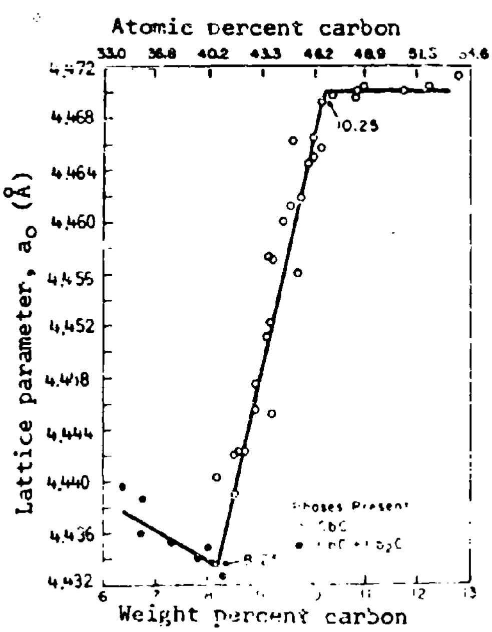
NIOBIUM-CARBON

GENERAL



Phase diagram of niobium-carbon system. [Ref. 19[illegible]]

A) NbC+L
B) Nb_2C+NbC
C) Nb_2C
D) (Nb)
E) α-Nb+L



Lattice parameters for niobium carbide, arc-cast samples:

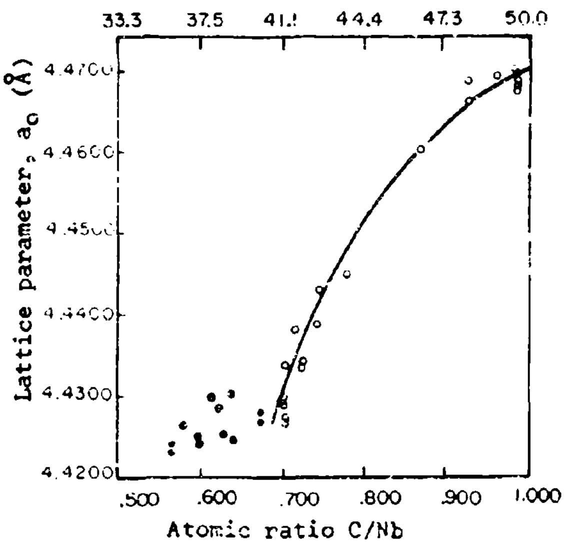
- o single phase NbC
- • double phase NbC+Nb_2C.

[Ref. 2[illegible]31]

Section 2

NIOBIUM-CARBON

GENERAL



Lattice parameters for powdered niobium carbide. The curve is a least squares fit of the data and follows the equation:

$$a_o = 4.4704 - 0.0239(1-x) - 0.3586(1-x)^2$$

where x is the atomic ratio C/Nb.

Sample Preparation

pressed: 100K - 200K psi
sintered: 3000°C for .5 hrs., or
1800°C for 38 hrs.

o single phase NbC
• double phase $NbC+Nb_2C$

[Ref. 20532]

Section 2
NIOBIUM-BORON

TRANSITION TEMPERATURE

Lattice Constant and Transition Temperature

At.% B	Phase	Lattice Constant (Å) a_o	b_o	c_o	Transition Temperature Tc(°K)	Symmetry	Notes Samples	Ref.
10	β	4.210	-	-	-	n.i.**	-	19932
10	β'	-	-	-	-	cubic	-	"
25	β"	-	-	-	-	n.i.**	-	"
25	NbB_m	-	-	-	-		8 min., 1650°C.	19752
40	Nb_3B_2	-	-	-	-		-	13014
50	NbB_n	-	-	-	-		21 min., 1530°C.	19752
50	"	-	-	-	-		9 min., 1810°C.	"
50	NbB	3.298	8.724	3.166	-	ortho	-	19625
50		-	-	-	6.00	"	Mo impurities.	9697
					8.25	-	Purified of Mo impurities.*	7666
50		-	-	-	6.94	-	Electron-beam melted & zone-refined.	15336
(+3% excess B)		-	-	-	5.51	-	"	15336
55		-	-	-	6.[illegible]	-	Sintered in argon, 1700-1750°C.	15336
57	Nb_3B_4	3.305	14.08	3.137	-	-	-	19625
57	"	-	-	-	<1.27	-	-	9697
59.3	Nb, NbB_2	-	-	-	4.60	-	"	15336
67.0	NbB_2+Nb_3B_4	3.110±.002	-	3.264±.002	-	-	Heated w/86% B, 22 min., 1565°C.	19752
67.0	NbB_2	3.085±.002	-	3.311±.002	-	hex	-	"
67.0	"	-	-	-	<1.27	"	-	9697

*Hulm and Mathias obtained T_c = 6.0°K [9697] and in a latter work [7666] removed the molybdenum impurities and obtained T_c = 8.25°K.
**n.i. = not indentified.

Section 2

NIOBIUM-CARBON

TRANSITION TEMPERATURE

Lattice Constants and Transition Temperatures

At.% C	Phases	Symmetry	Lattice Constants (Å) a_o	Lattice Constants (Å) c_o	Transition Temperature T_c(°K)	Notes	Ref.
25.9	$Nb+Nb_2C$	hexagonal	3.117	4.955	-	-	Hansen
28.5	-		-	-	9.2	Arc melted	9696
30.5	$Nb \rightleftarrows Nb_2C$		3.126 ±.001	4.965 ±.001	-	-	20533
32.4	Nb_2C+NbC		3.1194	4.9663	-	-	20531
32.4	-		-	-	9.2	Arc melted	9696
33.0	Nb_2C		-	-	9.18	Induction measurement.	9695
33.5	$NbC_{.51}$		-	-	<1.98	Heated at 2000°C.	9696
36.2	Nb_2C+NbC	-	3.1280 ±.0002	4.9722 ±.0003	-	-	20533
36.4	$NbC+Nb_2C$	cubic	4.4244	-	-	-	20532
39.7	$Nb_2C \rightleftarrows NbC$	hexagonal	3.1270 ±.0007	4.9710 ±.0005	-	-	20533
40.9	NbC	cubic	4.4281 ±.0001	-	-	-	"
41.1			-	-	≤1.05	Susceptibility measurement on powders heated 2000°C, 10^{-5}mmHg 2-24 hours.	18737
42.9			-	-			
43.6			-	-			
44.1			-	-			
44.7			-	-	1.05		

Section 2

NIOBIUM-CARBON

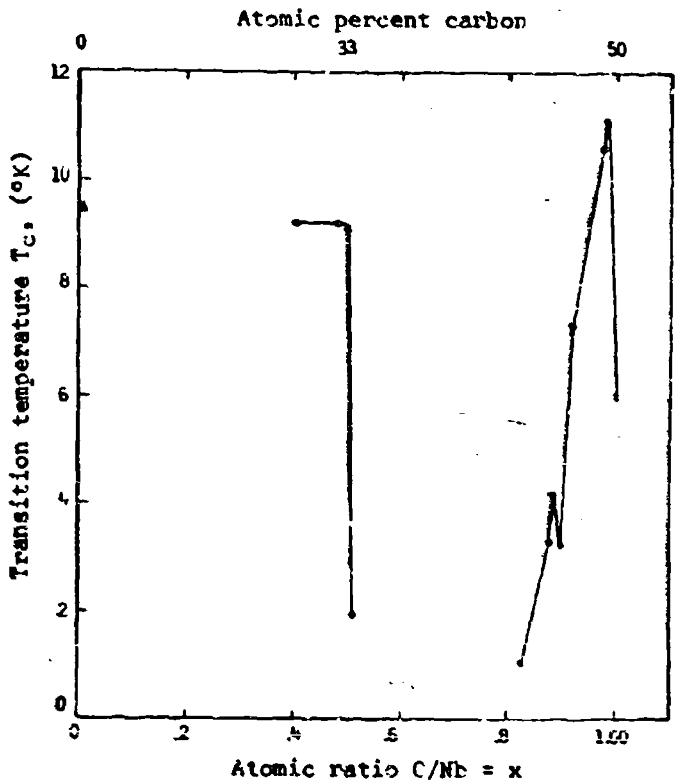
TRANSITION TEMPERATURE

Lattice Constants and Transition Temperatures
(Continued)

At.% C	Phases	Symmetry	Lattice Constants (Å) a_o	Lattice Constants (Å) c_o	Transition Temperature T_c(°K)	Notes	Ref.
46.5	NbC	cubic	4.4605	-	-	-	20533
46.75			-	-	3.5	Susceptibility measurement on powders heated 2000°C, 10^{-5}mmHg 2-24 hours.	18737
46.83			-	-	4.2		
46.89			-	-	3.2		
47.9			-	-	7.3		
49.18			-	-	10.6		
49.36			-	-	11.1		
49.41			-	-	"		
49.8			4.4702±.0001	-	-	-	20533
50.0			4.61	-	-	-	13014
50.0			-	-	6.0	Induction measured	9695

Section 2
NIOBIUM-CARBON

TRANSITION TEMPERATURE

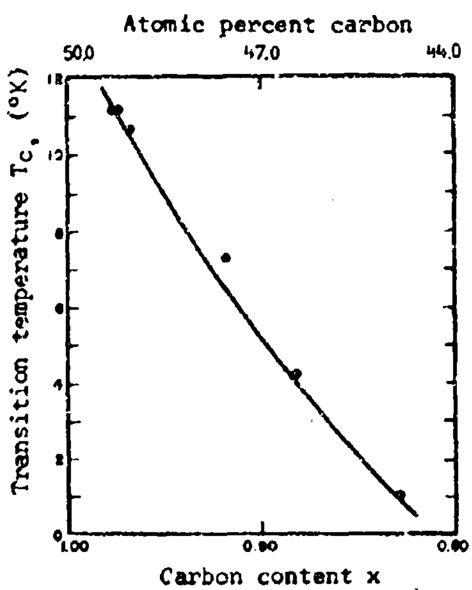


Plot of the data in the preceding table. Measurements are not available at x = .4; between x = .51 and x = .70 no transition temperature is reported. Data in this graph represents the following authors:

- Δ De Sorbo, W. [Ref. 13366]
- o Giorgi, A.W., et al. [Ref. 9606]
- • Giorgi, A.W., et al. [Ref. 18737]
- x Hardy, G.F. and J.K. Hulm [Ref. 9695]

Section 2
NIOBIUM-CARBON

TRANSITION TEMPERATURE

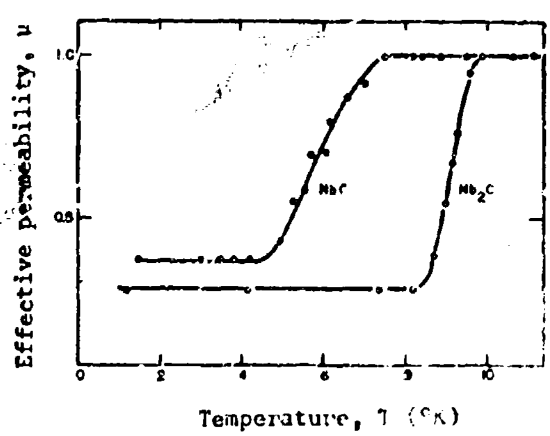


Transition temperature of niobium carbide as a function of the carbon content x, NbC_x.

Plot of Giorgi's data [Ref. 18737]

Transition curves for arc-melted NbC and Nb_2C samples, measured in a 26 Oe field.

[Ref. 9095]



Section 2

NIOBIUM-BORON

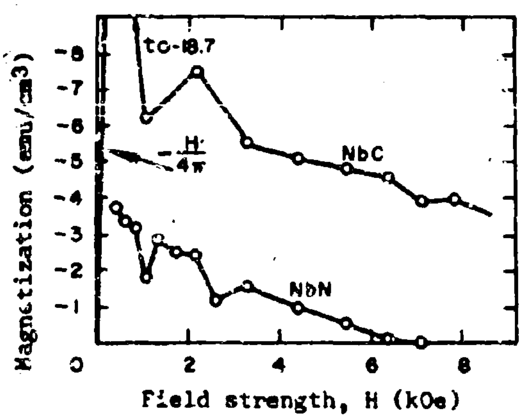
CRITICAL FIELD

Critical Field

At.% B	H_c, kGauss (4.2°K)	Notes: Symmetry	Notes: Samples	Ref.
50	4.45	orthorhombic β-MoB type	Electron beam melted & zone refined. Impurities: Ta 2000 ppm, others <100 each.	12621
50(+3% excess B)	5.05	"	"	
55	8.00	Nb, NbB	Sintered in argon at 1700-1750°C. Impurities: Ta 500 ppm Fe 100, others <50 each.	
59.3	4.8	N, NbB_2	"	

NIOBIUM-CARBON

MAGNETIZATION



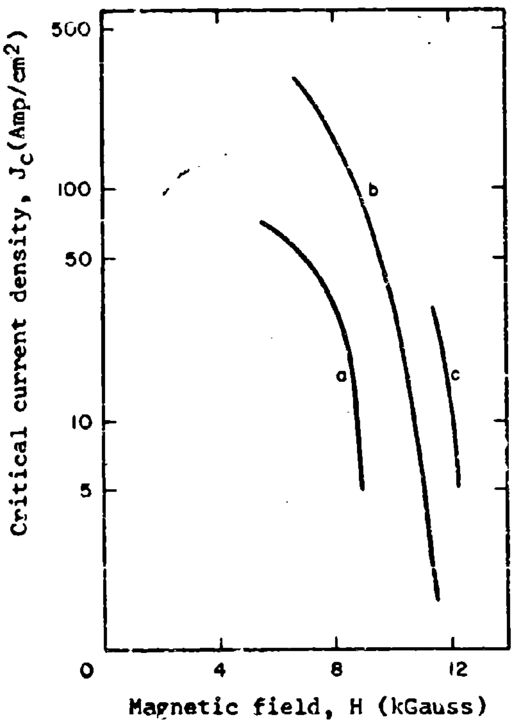
Magnetization as a function of applied field. Niobium carbide sample at 4.2°K. NbN curve is shown for comparison.

[Ref. 21847]

Section 2

NIOBIUM-CARBON

CURRENT DENSITY



Critical current density for two $NbC_{0.985}$ samples, as a function of external field. The samples were prepared by hot pressing of powders.

Impurities	T, (°K)
a) 0.6%	1.4
b) 0.3%	4.2
c) 0.6%	4.2

[Ref. 21780]

Section 2

NIOBIUM-BORON AND NIOBIUM-CARBON

SEMICONDUCTING PROPERTIES

Electrical and Thermal Properties

Electrical Resistivity $\rho(\mu\Omega\text{-cm})$	Thermal Conductivity $K(W/cm^{\circ}K)$	Thermoelectric emf $\mu V/^{\circ}C$	Hall Coefficient $R\ (10^{-4}cm^3/coul)$	Notes	Ref.
		NbB_2			
12	-	-	-1.0	-	3803
12-65	-	(α) 4.3	-	-	"
28-65	0.17	-	-	-	18179
32	-	-	-	-	11599
34	-	(α)-1.4	-2.1†	-	3803
35	0.167	-	-	25°C	18169
-	0.197-.259	-	-	200°C	"
65.5*	-	-	-	-	6778
-	-	(S)-3.7	-	Arc melted	14991
-	-	(S)-1.2	-	Annealed	"
		NbB			
64	-	-	-	-	11599
		NbC			
51.1	-	(α)-4.0	-1.32**	-	3803
74.0	0.14	-	-	25°C, sintered powder.	18179
150.0	-	-	-	-	6778
204.0	0.134	-	-	a-axis, polycrystalline, dense powder.	12288
-	0.14	-	-	25°C, sintered powder.	18169
-	0.37	-	-	1900°, S.P.	"
-	-	(S)-9.4	-	Arc melted.	14991
-	-	"	-	Annealed.	"

† $\delta = +51.1 \times 10^{-23}(cm/V^2sec^2)$

** $\delta = +11.4$ " "

$$\delta = \frac{R}{e\rho^2} = n_e\mu_e^2 - n_h\mu_h^2$$

n is the carrier concentration and μ is the mobility

* Thermal coefficient of resistivity. α = +0.12(%/deg)

AIR FORCE MATERIALS LABORATORY
RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND

ELECTRONIC PROPERTIES INFORMATION CENTER

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NIOBIUM-BORON

SEMICONDUCTING PROPERTIES

Electrical Resistivity

At.% B	(μΩ-cm)	ρ_{T_c}/ρ_{300}	Notes: Crystallography	Notes: Samples	Ref.
50	9.72	.0261	orthorhombic β-MoB type	Electron beam melted & zone refined. Impurities: Ta 2000 ppm, others <100 each.	12621
50(+3% excess B)	10.57	.0279	"	"	
55	8.120	.0345	Nb, NbB	Sintered in argon at 1700-1750°C. Impurities: Ta 500 ppm, Fe 100, others <50 each.	
58.3	14.76	.0366	N, NbB_2	"	

NIOBIUM-CARBON

SEMICONDUCTING PROPERTIES

Electrical and Thermal Properties

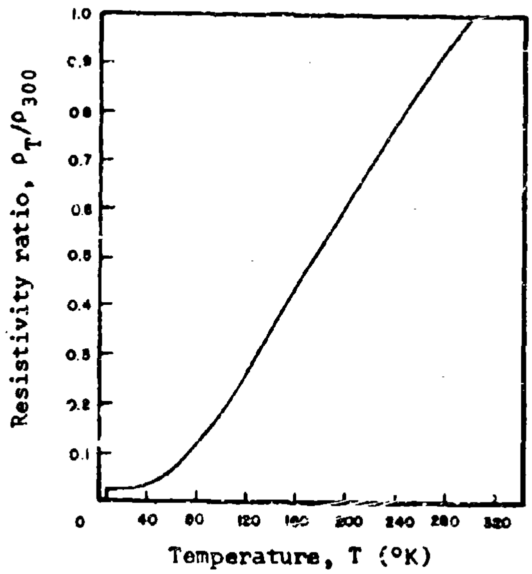
Formula	Lattice Constant a_0(Å)	Electrical Resistivity (μΩ-cm)	Thermal Conductivity χ (10^{-2}W/cm°K)	Thermoelectric Effect (μV/°K)
$NbC_{.710}$	4.431	171.7	9.0 ± 0.7	-1.9 ± 0.1
$NbC_{.750}$	-	150.0	9.7 ± 0.7	-2.1 ± 0.1
$NbC_{.808}$	-	151.9	10.2 ± 1.2	-3.4 ± 0.4
$NbC_{.855}$	-	135.2	10.7 ± 1.2	-5.8 ± 0.6
$NbC_{.908}$	4.464	89.8	11.2 ± 0.7	-5.5 ± 0.3

[Ref. 21271]

Section 2

NIOBIUM-BORON

ELECTRICAL RESISTIVITY



Resistivity ratio as a function of temperature for electron-beam melted, zone-refined NbB. Measurements on sintered samples show a similar curve.

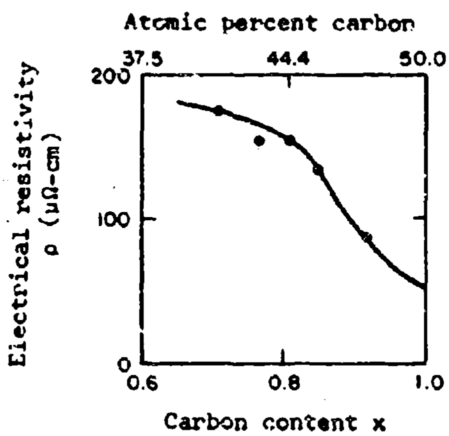
[Ref. 15336]

NIOBIUM-CARBON

ELECTRICAL RESISTIVITY

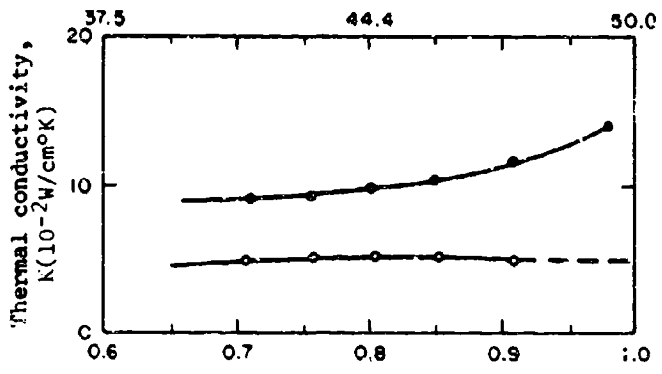
Electrical resistivity of NbC_x. Powders were pressed and sintered at 10^{-4} - 10^{-5}mm Hg and 2200-2400°C.

[Ref. 21271]



NIOBIUM-CARBON

THERMAL CONDUCTIVITY

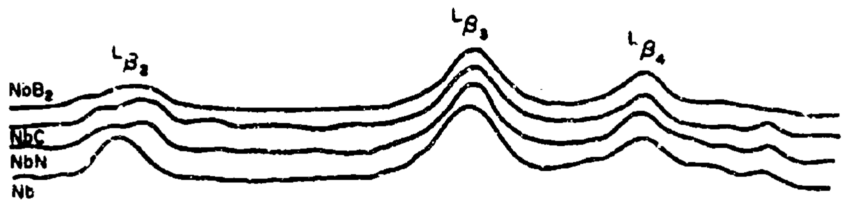


Thermal conductivity of NbC_x powders which were pressed and sintered at 10^{-4} - 10^{-5}mm Hg and 2200 - 2400°C.

[Ref. 21271]

NIOBIUM-BORON AND NIOBIUM-CARBON

PHOTON EMISSION PROPERTIES



The L series spectra for NbB_2 and NbC. The curves for NbN and pure Nb are given for comparison.

[Ref. 16346]

Section 2

NIOBIUM-BORON AND NIOBIUM-CARBON

PHOTON EMISSION PROPERTIES

L line intensities for Nb compounds.

Line	Nb	NbN	NbC	NbB_2
$L_{\alpha 1}$	100	100	100	100
$L_{\alpha 2}$	11	11	11	11
$L_{\beta 1}$	60.0	60.5	61.0	62.0
$L_{\beta 3}$	9.9	9.5	9.9	10.2
$L_{\beta 2}$	5.3	4.0	4.0	3.5
$L_{\gamma 1}$	2.0	1.47	1.48	1.40
N_{IV}	0.56	0.39	0.39	0.36
N_{V}	1.27	0.91	0.90	0.77
$N_{IV}+N_{V}$	1.83	1.30	1.29	1.13

[Ref. 16346]

Relative values of the variation of the $L_{\beta 2}$ and $L_{\gamma 1}$ lines for equal $L_{\beta 4}$ intensities.

Line	Nb	NbN	NbC	NbB_2
$L_{\beta 2}$	100	71.5	72.9	68.5
$L_{\gamma 1}$	37	26.3	27	27.6

[Ref. 16346]

Section 2

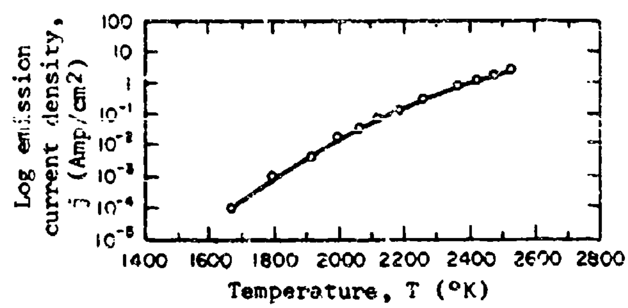
NIOBIUM-BORON AND NIOBIUM-CARBON

THERMIONIC EMISSION PROPERTIES

Work Function ϕ(eV)	Richardson's Constant A (Amp/cm^2 deg^2)	Current Density J_c (Amp/cm^2)	Notes	Ref.
		NbC		
2.23	$\sim 10^{-6}$	-	-	11031
4.02	-	-	300°K	
3.74	-	-	1400°K	
3.72	-	-	1800°K	
3.58	-	3.6	2000°K	
		NbB_2		
3.65	-	-	-	16424

NIOBIUM-CARBON

THERMIONIC EMISSION PROPERTIES



Emission current density for niobium carbide ~100μ thick, based on (1) 30μ strips of tungsten and tantalum and (2) tungsten and tungsten carbide wires. The properties show little dependence on the base. The samples were treated and measurements taken after heating to 2400°K.

Heating	Work Function
1500 - 1800°K	reduced from 4.4 to 3.8 ev
1800 - 2400°K	raised from ~3.6 to 4.2 ev

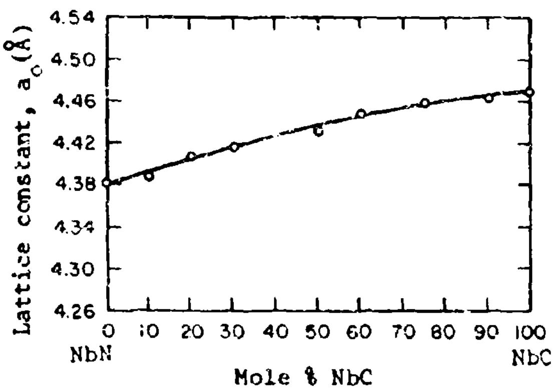
[Ref. 19231]

SECTION 2
NIOBIUM-CARBON-NITROGEN SYSTEMS

NIOBIUM ALLOYS AND COMPOUNDS

NIOBIUM-CARBON-NITROGEN

GENERAL

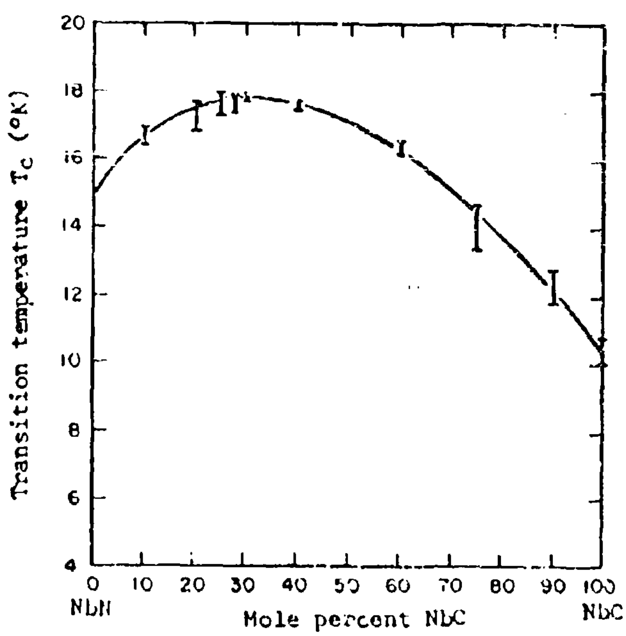


Lattice constants for the NbN-NbC system. The samples were cold pressed compacts, sintered between 2000-2400°C in nitrogen.

[Ref. 21840]

TRANSITION TEMPERATURE

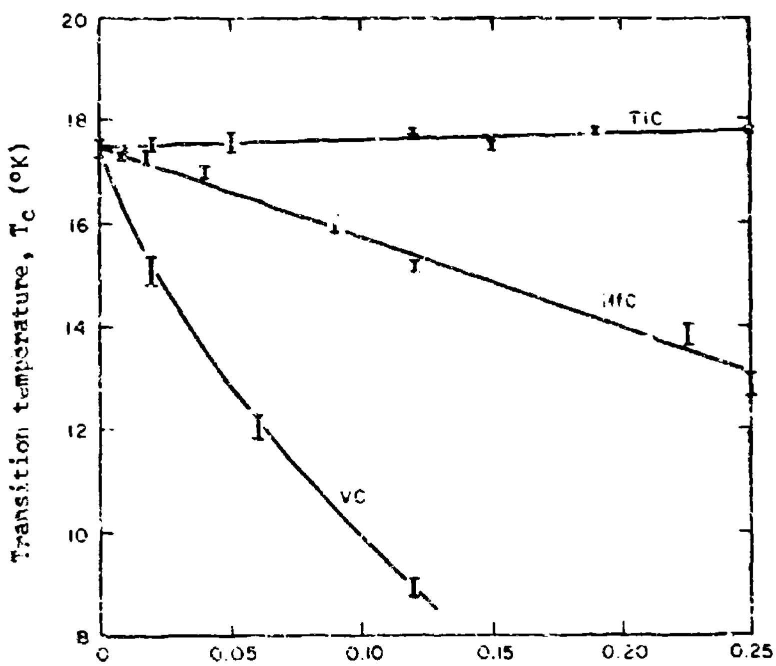
Transition temperature for the system NbN-NbC. Samples were cold pressed and sintered 2000 - 2400°C in nitrogen.



[Ref. 21844]

NIOBIUM-CARBON-NITROGEN-M

TRANSITION TEMPERATURE



Transition metal-carbide content x

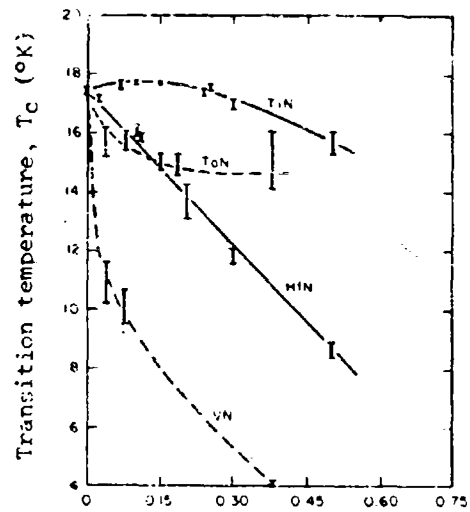
Transition temperature for the system $(NbN)_{0.75}(NbC)_{0.25-x}(MC)_x$ where M is Ti, Hf or V.

[Ref. 21844]

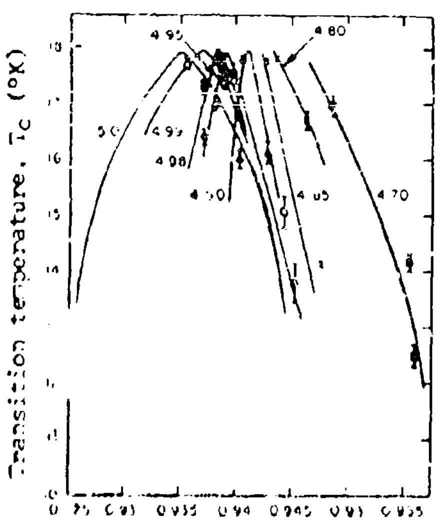
NIOBIUM-CARBON-NITROGEN-M

TRANSITION TEMPERATURE

Transition temperature for the system $(NbN)_{0.75-x}(NbC)_{0.25}(MN)_x$ where M is Ti, Ta, Hf, or V.



Transition metal nitride content x



Effective diam. of transition metal in compound

Transition temperature for pseudo-binary and ternary nitride-carbide compounds. The numbers represent the e/a ratio for the compound.

ALLOY SYSTEMS STUDIED	TRANSITION METAL e/a RATIO
NbN-NbC-TiC	4.99
NbN-NbC-TiN	4.98
NbN-NbC-HfC	4.95
NbN-NbC-HfN	4.90
NbN-ZrN-TiN	4.85
NbN-ZrN	4.80
NbN-TiC	4.70
NbN-NbC	

[Ref. 21846]

NIOBIUM-CARBON-NITROGEN

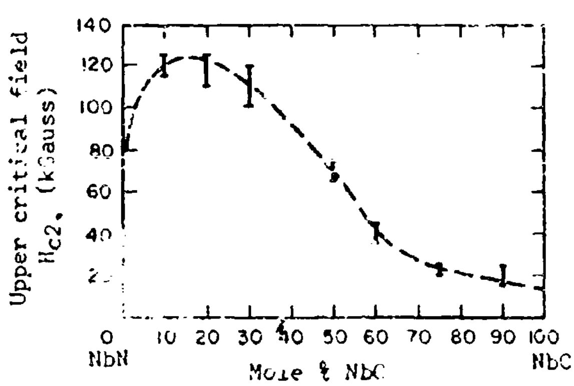
TRANSITION TEMPERATURE

Compound	Transition Temperature T_c(°K)	Notes	Ref.
NbC/NbN+	8.5 - 17.3	Whiskers 2μ-100μ diam, [111] orientation.	21847
$NbC_{0.3}N_{0.7}$	17.8	-	21644
NbN-NbC-NbO	>20	Prepared by chemical vapor deposition.	21843

+ $\rho(20°K) = 6 \times 10^{-5}$ Ω-cm

NIOBIUM-CARBON-NITROGEN

CRITICAL FIELD

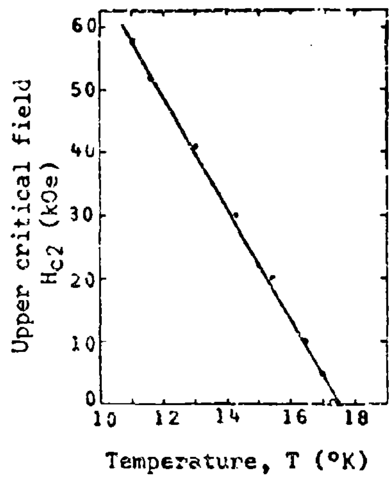


Upper critical field for NbN-NbC system. The samples were cold pressed compacts, sintered between 2000-2400°C in nitrogen.

[Ref. 21840]

NIOBIUM-CARBON-NITROGEN

CRITICAL FIELD



Upper critical field for a 5.8μ diam. NbC/NbN whisker as a function of temperature. These mixed structures were formed in the [111] direction when carbon and nitrogen were both present. [Ref. 21847]

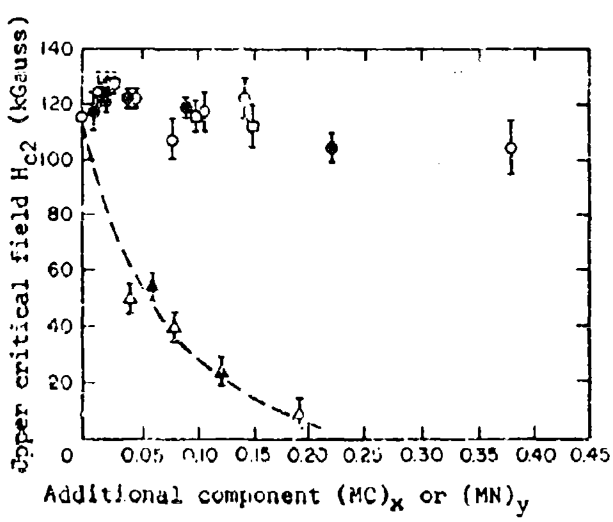
$$\left(dH_{c2}/dT\right)_{T_c} = -9 \text{ kOe}/°K$$

H||I

NIOBIUM-CARBON-NITROGEN-M

CRITICAL FIELD

For the following graph the samples were cold pressed compacts, sintered between 2000-2400 in nitrogen.



The upper critical field for the following systems $(NbN)_{0.75}(NbC)_{0.25-x}(MC)_x$ or $(NbN)_{0.75-y}(NbC)_{0.25}(MN)_y$ as a function of the additional component.

NbN-NbC-HfN — NbN-NbC-HfC
NbN-NbC-TiN — NbN-NbC-TiC
NbN-NbC-VN — NbN-NbC-VC

[Ref. 21844]

NIOBIUM-CARBON-NITROGEN

CRITICAL FIELD

Compound	Critical Field (kOe) H_{c1}	H_c	H_{c2}	Notes	Ref.
NbC/NbN	.1	1.7	~110*	Whiskers 2μ-100μ diam, [111] orientation.	21847
$NbC_{0.2}N_{0.8}$	-	-	120	-	21847

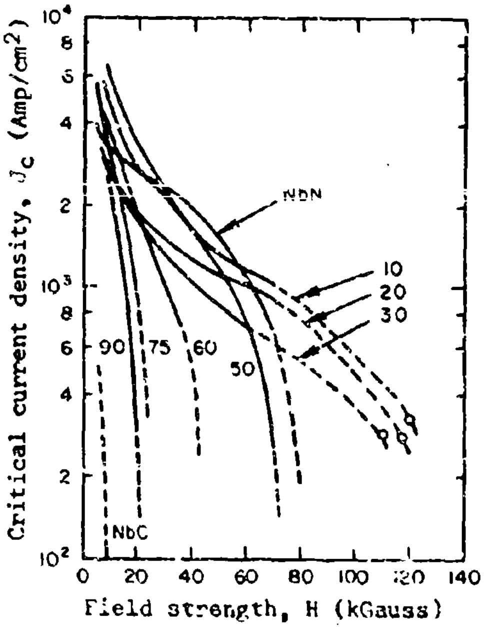
$$* \left(\frac{dH_{c2}}{dT}\right)_{T_c} = -9\left(\frac{kOe}{°K}\right)$$

NIOBIUM-CARBON-NITROGEN

CURRENT DENSITY

Critical current density for NbN-NbC system as a function of field strength for different mole percentages of NbC. The samples were cold-pressed compacts, sintered between 2000-2400°C in nitrogen atmosphere.

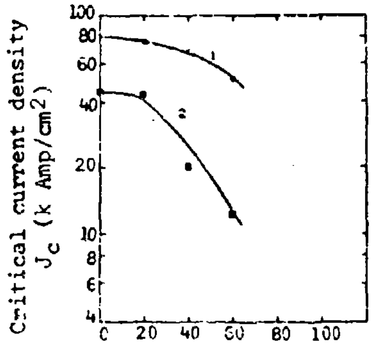
o pulsed field data



[Ref. 21840]

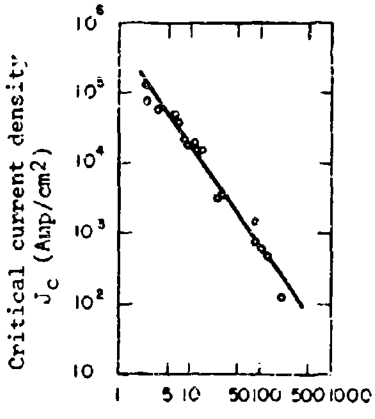
NIOBIUM-CARBON-NITROGEN

CURRENT DENSITY



Critical current density as a function of field strength for NbC/NbN, [111] oriented whiskers. Data taken at 4.2°K.

1) 3.5μ diameter
2) 5.8μ diameter [Ref. 21847]

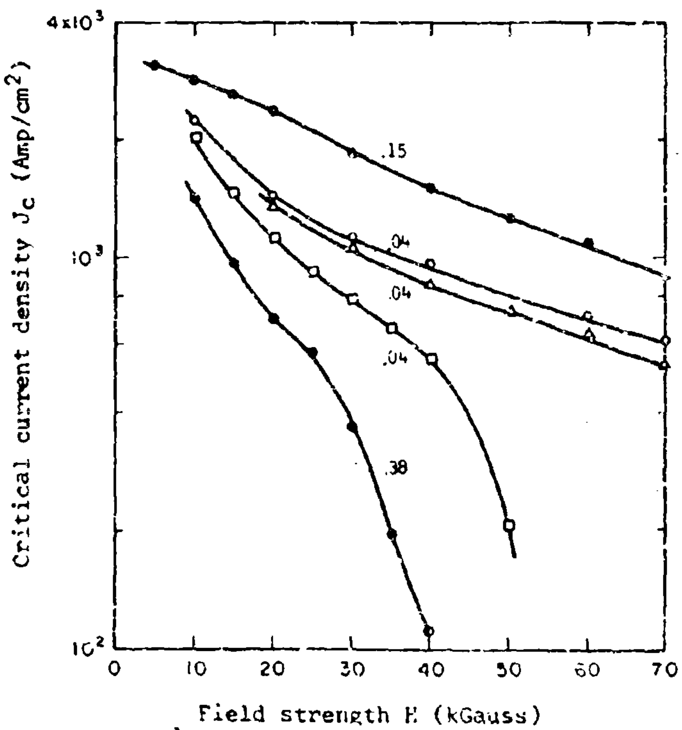


Critical current density for NbC/NbN, [111] oriented whiskers, as a function of sample diameter. Measurements are taken at 4.2°K.

[Ref. 21847]

NIOBIUM-CARBON-NITROGEN-M

CURRENT DENSITY



Critical current density for the system $(NbN)_{0.75-x}NbC_{0.25}(MN)_x$ as a function of field strength, where M is Hf, V or Ti. The numbers on the curves represent the transition metal nitride content in x.

- o NbN-NbC
- Δ NbN-NbC-HfN
- □ NbN-NbC-VN
- ● NbN-NbC-TiN

[Ref. 21844]

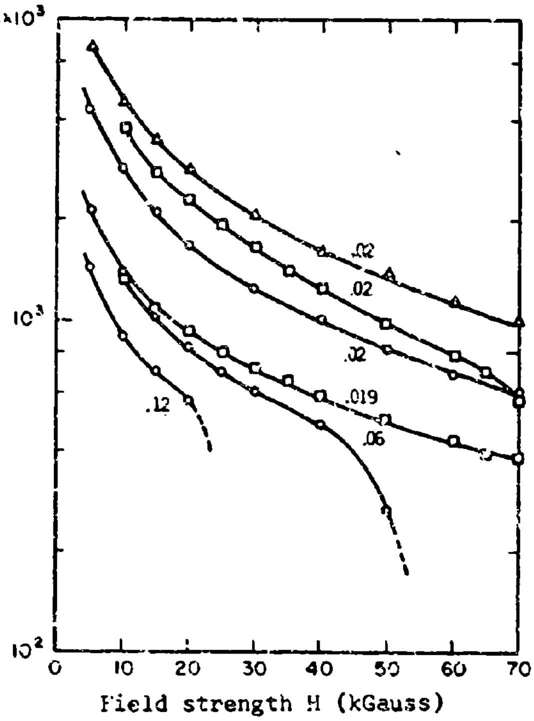
NIOBIUM-CARBON-NITROGEN-M

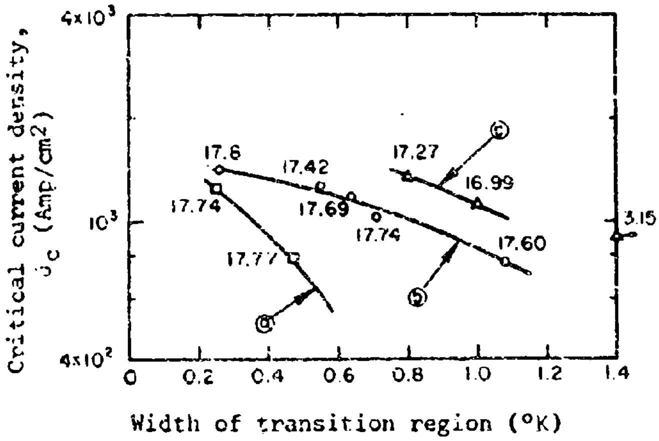
CURRENT DENSITY

Critical current density for the system $(NbN)_{0.75}(NbC)_{0.25-x}(MC)_x$ where M is Ti, Hf or V. The numbers on the curves represent the transition metal carbide content in x.

□ TiC
Δ HfC
o VC

[Ref. 21844]





The critical current density is given for three pseudo-ternary compounds and is plotted against the width of the transition region. This region of transition is an indication of the deviation from stoichiometry. The numbers indicate the midpoints of the regions.

(a) NbN-NbC-TiN
(b) NbN-NbC-TiC
(c) NbN-NbC-HfC

[Ref. 21844]

SECTION 2

NIOBIUM-NITROGEN &

NIOBIUM-OXYGEN SYSTEMS

NIOBIUM ALLOYS AND COMPOUNDS

NIOBIUM-NITROGEN AND NIOBIUM-OXYGEN SYSTEMS

GENERAL

Nb-N The transition temperature for a niobium-nitrogen system in the $Nb_{1.0}N_{1.0}$ region is near 16°K. As the nitrogen content is reduced to the Nb_2N region, T_c apparently decreases to zero. With further reduction of the nitrogen content, the transition temperature begins to rise and approaches that of pure niobium.

Two notations have been used to differentiate the various compounds in the niobium-nitrogen systems. Brauer and Jander (20714) in their 1952 work assign the following notations NbN(I), NbN(II), and NbN(III) to the compositions $NbN_{1.00}$, $NbN_{\sim 0.95}$, and $NbN_{\sim 0.87-0.94}$ respectively. Schoenberg in 1954 uses the following naming scheme:

α phase	Nb+N
β	$NbN_{0.40-0.50}$
γ	$NbN_{\sim 0.80-0.90}$
δ	$NbN_{\sim 0.95}$
ε	$NbN_{1.00}$.

The exact nature of the transition from normal to superconducting state is in doubt in two composition regions. First near the $NbN_{1.00}$ Schroeder [9655] claims that T_c drops below 1.94°K. Rogener composition data do not show this effect, and two earlier papers, Ziegler and Young (13330) and Milton (19468), can not claim an exact $NbN_{1.00}$ composition for their samples. Schroeder cites data from Brauer stating that at lower temperatures of formation, the NbN(I), NbN(II) and NbN(III) regions are broadened by beginning the sample preparation at lower nitrogen content.

The other area of doubt is found in the Nb_2N region. No experimental evidence can be found for a transition temperature above 1.94°K [9655]. However,

NIOBIUM-NITROGEN AND NIOBIUM-OXYGEN SYSTEMS

GENERAL

Samsonov and Neshpor [10725] predict $T_c = 9.5°K$ for Nb_2N based upon a relationship between T_c and $\frac{1}{Nn}$ where N is the principle quantum number and n is the number of electrons of the incomplete d-level.

The following value is given for NbN, [21847]

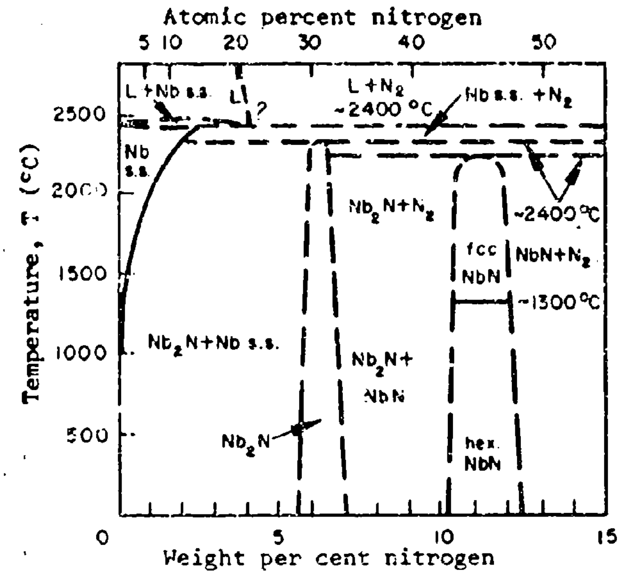
$$\frac{dH_{c2}}{dT_c} = -10 \frac{kOe}{°K.}$$

Nb-O Three distinct niobium oxides are formed, NbO (14.69 wt.% O), NbO_2 (25.89 wt.% O) and Nb_2O_5 (30.09 wt.% O). However, none of these show any promise as superconducting materials. An attempt to find the transtion temperature of NbO has failed to show a T_c above 1.2°K (9695). Below the solubility limit of oxygen in niobium, i.e., from .25 to 1.0 wt.% oxygen, the solid solution Nb-O shows superconducting characteristics.

Samples up to .75 wt.% Oxygen were prepared by a gas absorption and diffusion technique. In the region of 1 wt.% O and above the samples were prepared by arc-melting Nb_2O_5 with Nb.

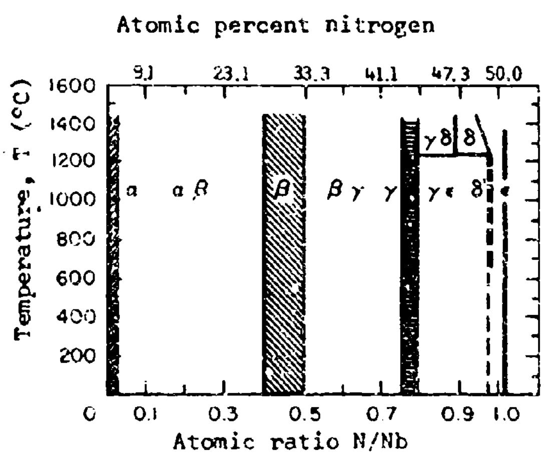
NIOBIUM-NITROGEN

GENERAL



s.s.: solid solution.

Probable phase diagram for niobium-nitrogen system at a pressure of one atmosphere nitrogen [Ref. 19928]

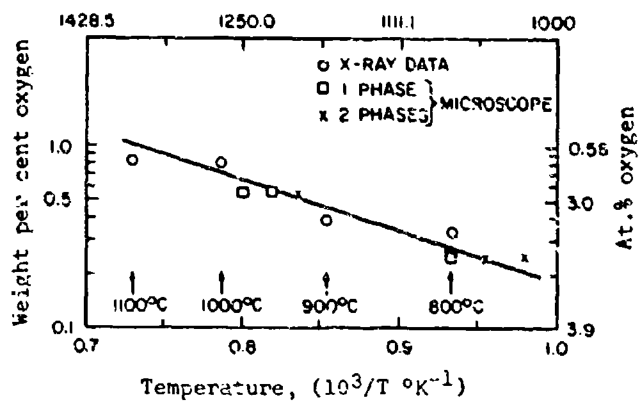


Tentative phase diagram for the niobium-nitrogen system.

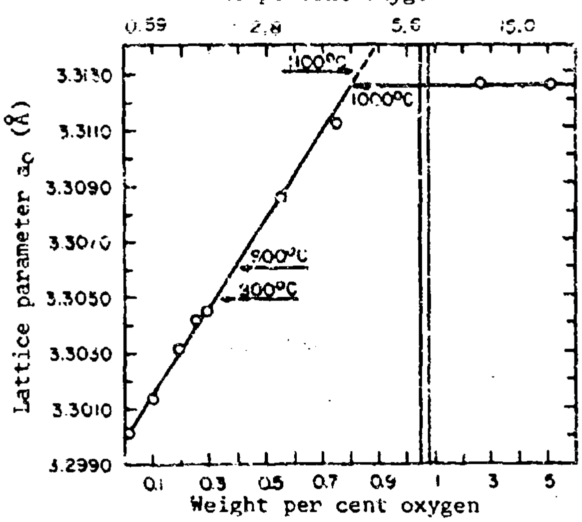
[Ref. 20719]

NIOBIUM-OXYGEN

GENERAL



Solubility of oxygen in niobium. The x-ray data were checked by metallographic examination on two samples: .25 wt.% O and .55 wt.% O.



Lattice parameters for the niobium-oxygen system. Up to .75% oxygen gas absorption and diffusion methods were used to prepare the samples. Above this region Nb and Nb_2O_5 were arc melted together to form the samples.

[Ref. 21113]

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NIOBIUM-NITROGEN

GENERAL

Lattice Constants

At.% N	Phase	Symmetry	Lattice Constants (Å) a_o	c_o	Notes	Ref.
0	α	bcc	3.3014 ± .0002	-	-	20714
15.9	α+β	hcp	3.056	4.956	-	
32.4	β	tetr	3.056	4.964	-	
42.9	"	tetr deformed	4.384	4.311	-	
44.4	"	"	4.385	4.332	-	
44.4	γ	hex	2.950	2.772	-	
44.5		fcc	4.39	-	4200 psi pressed powder, double sintered.	18467
45.0		tetr deformed	4.387	4.330	-	20714
46.5		fcc	4.386	-	Powder sample in pumped N at 1300°C	"
47.3		hex	2.958	2.779	-	20627
48.4		fcc	4.389	-	-	20714
48.7	δ	hex	2.968	5.535	-	20627
50.0	ε	"	2.956	11.275	-	20714

NIOBIUM-OXYGEN

GENERAL

The lattice constants for monoclinic α-Nb_2O_5 are given:

$$a_o = 21.34\ \text{Å}$$
$$b_o = 3.816\ \text{Å}$$
$$c_o = 19.47\ \text{Å}$$
$$\beta = 120^\circ\ 2'$$

[Ref. 17444]

NIOBIUM-NITROGEN

TRANSITION TEMPERATURE

Transition Temperature

At.% N	Transition Temperature T_c (°K) Midpoint	Width Onset	Complete	*	Notes	Ref.
0	8.97	9.4	8.5	-	-	9655†
.23	-		-	9.2	Wire, electron beam melted, heated in N.	13366
16.0	5.72	7.2	-	-	-	9655
32.4	-	<1.94	-	-	-	"
37.5	3.8	6.1	<1.94	-	-	9617**
39.1	-	-	-	10.8	-	
40.1	-	-	-	10.3	-	
42.1	-	-	-	11.0	-	
42.3	-	-	-	12.7	-	
42.8	7.2	-	-	-	Powder heated in N to 1450°C.	9695
43.2	-	-	-	13.6	-	9617
44.0	-	-	-	11.8	-	"
44.4	7.12	9.7	5.2	-	-	9655
44.6	-	-	-	12.6	-	9617
45.1	8.66	10.6	6.4	-	-	9655
45.4	15.0	16.2	12.2	-	Powder Nb, 16 atm N, 1450°C 5 hours.	18726
46.5	-	-	-	15.98	-	9617
47.3	-	15.25	14.7	-	Powder 1300°C N stream.	9299
47.7	-	-	-	14.13	-	9617
48.4	<1.94	10.62	-	-	-	9655
48.6	-	-	-	15.59	-	9617
48.7	-	-	-	14.7	-	
48.8	-	-	-	14.57	-	
49.0	-	-	-	15.63	-	
49.4	15.2	16.2	13.5	-	Powder Nb, 1 atm N, 1300°C 3 hours.	18726
49.7	-	-	-	15.23	-	9617
~50.0	-	-	-	< 1.94	-	9655
	15.9±0	-	-	-	Ammonia 1350-1500°, 20 min.	19468
	-	15.0	14.0	-	Stationary N, 1500°C, 1 hour.	
	16.0	16.7	14.6	-	Nb heated 4-4.5 hours at 1500°C in dry N.	13390

* Values in this column are not identified by their position in the transition curve.
** Sample specs are found on page 48-49
† Sample specs are found on page 52

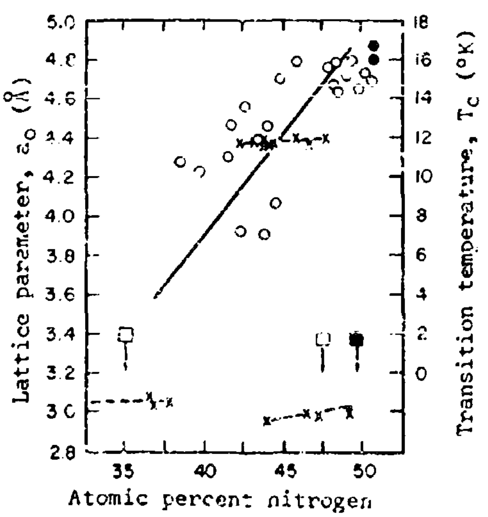
NIOBIUM NITROGEN

TRANSITION TEMPERATURE

Transition Temperature
(Continued)

At.% N	Transition Temperature T_c (°K) Midpoint	Width Onset	Complete	*	Notes	Ref.
~50.0	-	9.0	6.0	-	Film sputtered. DC argon glow discharge in $\sim 2\times10^{-2}$ torr at 2 Å/sec. Polished quartz substrate.	20628
50.3	-	-	-	14.47		9617
50.7	-	-	-	15.30		↓
51.2	-	-	-	14.93		↓

* Values in this column are not identified by their position in the transition curve.



A plot of data from preceding tables, showing the relationship of lattice constant a_o and transition temperature to nitrogen content. All curves are least squares approximations.

x - - - - - - - - a_o

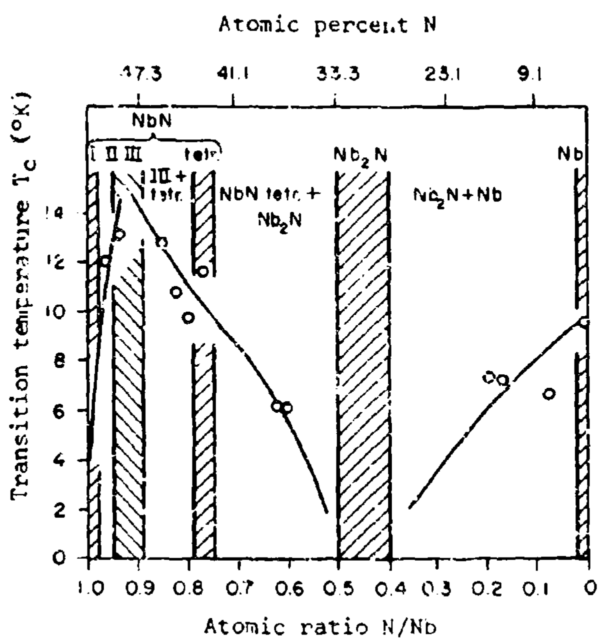
○ ———————— T_c

□ T_c <1.94

● T_c with the exact N content in doubt

NIOBIUM-NITROGEN

TRANSITION TEMPERATURE



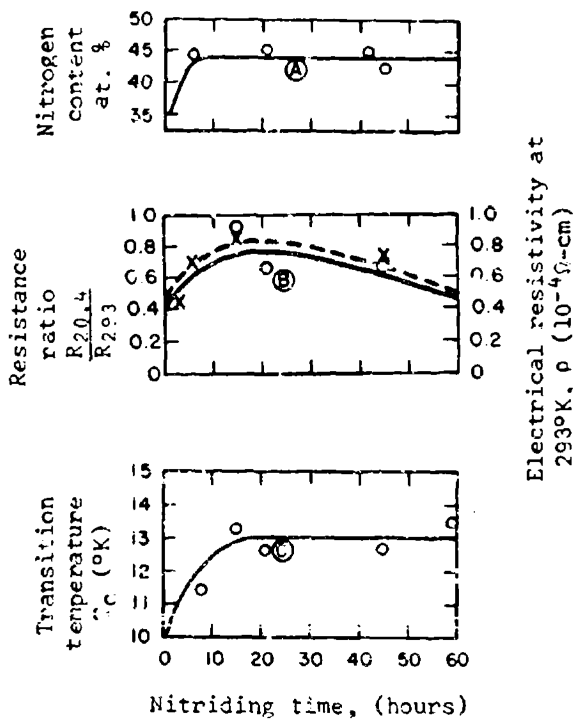
Temperatures at which the transition region begins at i.e., the onset of superconductivity, for the Nb-N system.

[Ref. 9655]

Two conditions during preparation of niobium nitride will affect its properties, first the nitrogen pressure and second the time the sample is left in the nitrogen atmosphere. The two sets of graphs which follow show the effects of these two parameters on the properties of the sample.

NIOBIUM-NITROGEN

TRANSITION TEMPERATURE



The effect of time in the nitrogen atmosphere on the properties of niobium-nitrogen systems.

A) nitrogen content

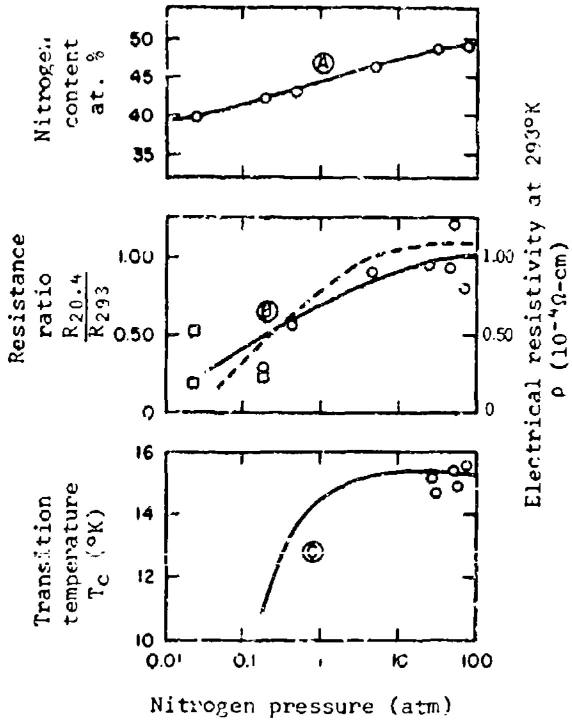
B) o———o, electrical resistivity
x - - - x, resistance ratio

C) transition temperature

[Ref. 961?]

NIOBIUM-NITROGEN

TRANSITION TEMPERATURE



The effect of nitrogen pressure during preparation, on the properties of niobium-nitrogen systems.

A) nitrogen content

B) o————o, electrical resistivity
x - - - - x, resistance ratio

C) transition temperature

[Ref. 9617]

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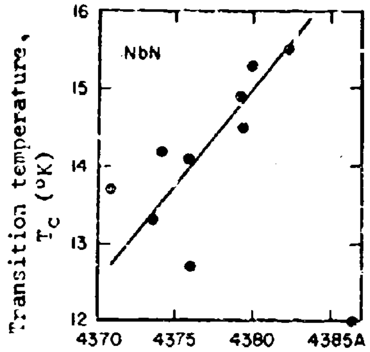
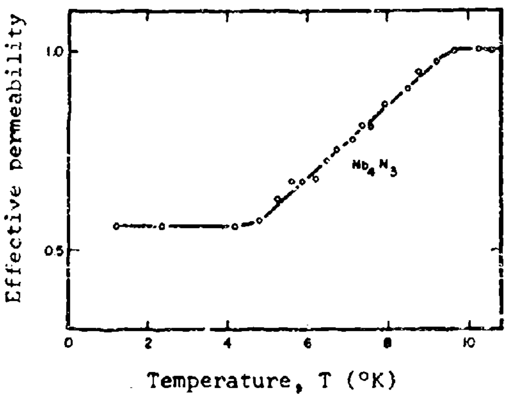
NIOBIUM-NITROGEN

TRANSITION TEMPERATURE

Transition temperature as a function of lattice constant for fcc niobium nitride.

[Ref. 9617]





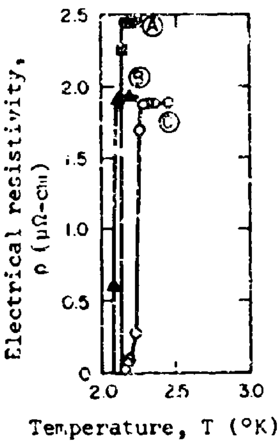
Transition curve for tetragonal Nb_4N_3 in a 26 Oe field.

[Ref. 9695]

Electrical resistivity as a function of temperature for:

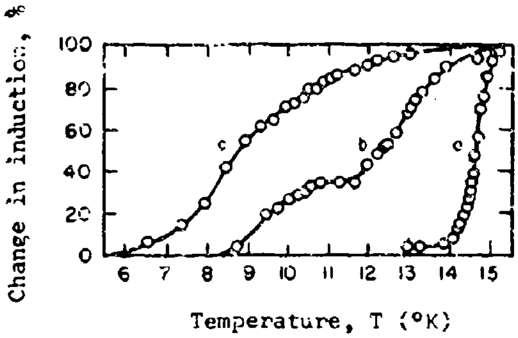
A) 0.33 at.% N, He quenched
B) 0.33 at.% N, vacuum quenched
C) 1.64 at.% N, vacuum quenched

[Ref. 13366]



NIOBIUM-NITROGEN

TRANSITION TEMPERATURE



Transition curves for three niobium nitride samples:

(a) 47.2 at.% N, prepared in nitrogen stream for not less than 8 hours at 1350°C. Data taken on warming and cooling.

(b) 44.0 at.% N, prepared in static N for not less than 8 hours at 1200°C. Data taken on warming only.

(c) 27.2 at.% N, prepared in static N for not less than 8 hours at 1180°C. Data taken on warming only.

[Ref. 9299]

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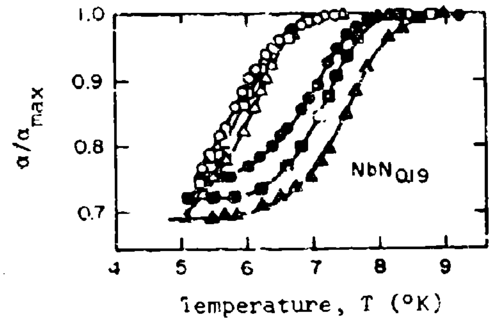
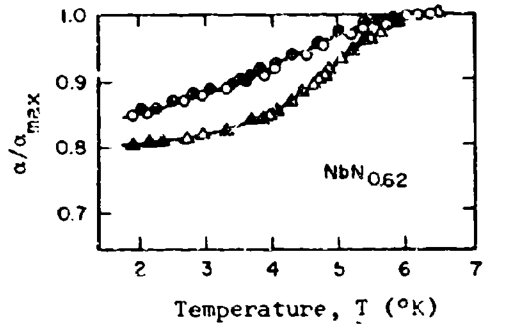
NIOBIUM-NITROGEN

TRANSITION TEMPERATURE

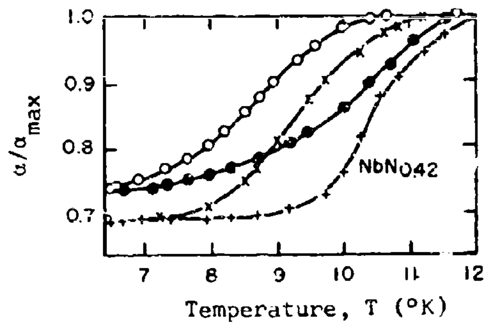
Transition curves for niobium-nitrogen systems.



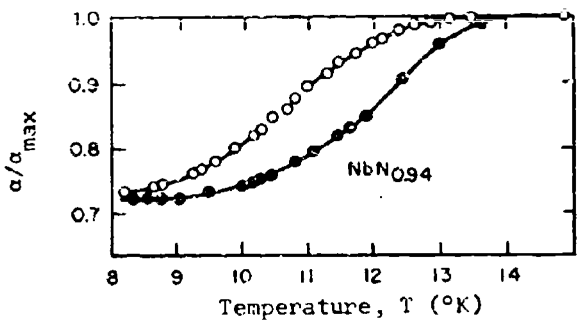
Nb added to NbN and treated 3 hrs. at 1450°C in one atmosphere pressure argon; hcp structure.



Nb added at NbN and treated 3 hrs at 1450°C in one atmosphere pressure argon; tetragonal structure.



Powdered Nb in stationary N at one atmosphere pressure, 4-5 hrs., 1300-1450°C; tetragonal structure.



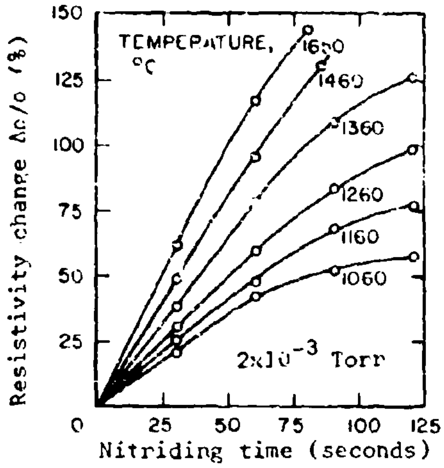
Powdered Nb in stationary N at one atmosphere pressure, 4-5 hrs., 1300-1450°C; fcc structure.

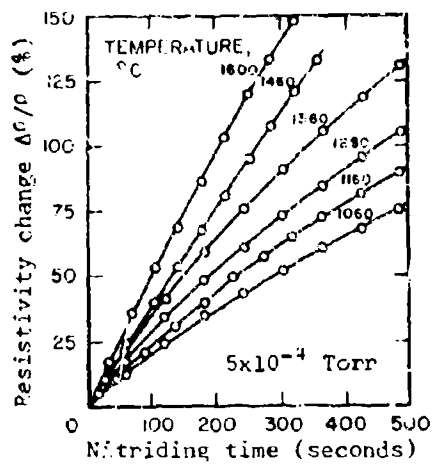
WARMING	COOLING	FIELD (Oe)
○	●	1450
□	■	1090
△	▲	72.5
×	+	36.2

[Ref. 9655]

NIOBIUM-NITROGEN

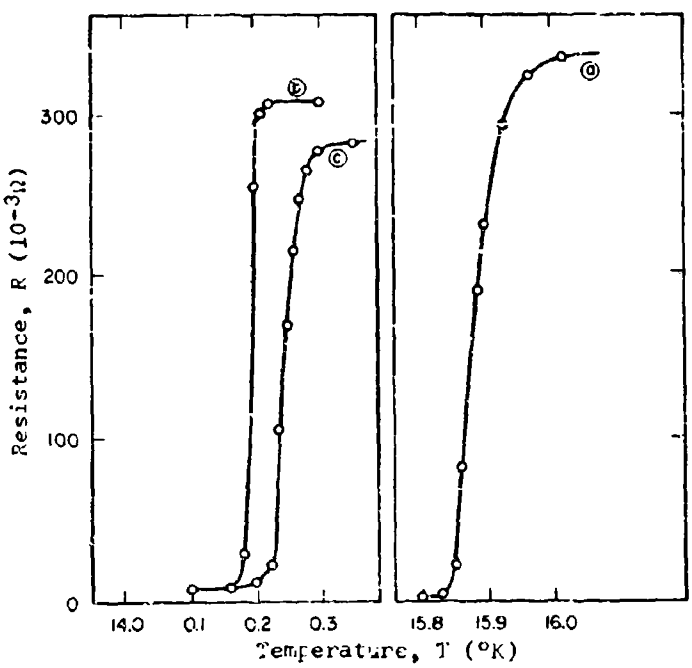
TRANSITION TEMPERATURE





Change in resistivity as a function of nitriding time, temperature, and pressure. Data were taken at 10°C, $\rho_{10°C}$ = 13.96 (μΩ-cm).

[Ref. 21850]



Superconductive transition of three niobium nitride samples:

a. Prepared in ammonia, 20 minutes at 1350-1500°C.

b. Prepared in nitrogen, 1 hour at 1500°C.

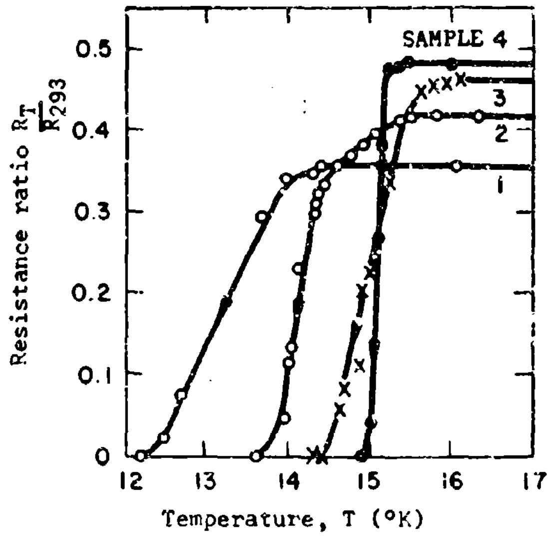
c. Prepared in nitrogen, 1 hour at 1500°C.

[Ref. 19468]

NIOBIUM-NITROGEN

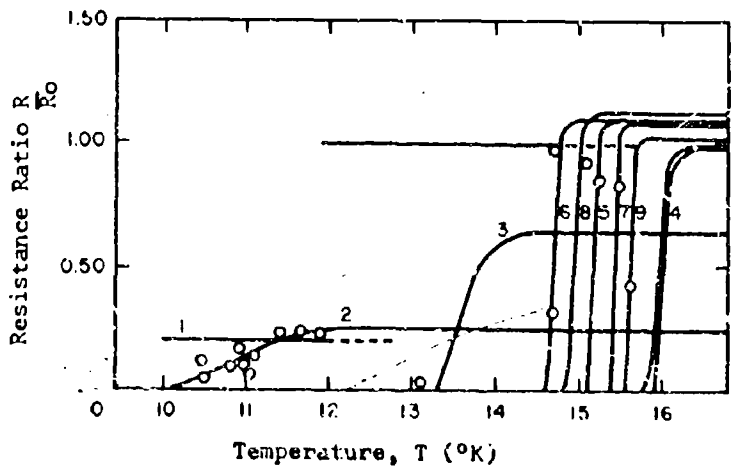
TRANSITION TEMPERATURE

Resistance ratio curves for four niobium nitride samples. I = 0.017 Amp.



Sample	Nitrogen at.%	N-Pressure atm.	Time Hours	Temperature °C
1	44.8	1.2	10	1450 - 1500
2	46.2	2	30	
3	48.3	9	50	
4	49.7	40	45	

[Ref. 10728]



Transition curves for NbN formed at 1470°C, under different nitriding pressures.

Nitrogen Pressure (atm)	
1) 0.025	6) 32
2) 0.20	7) 52
3) 0.47	8) 55
4) 5.0	9) 80
5) 28.0	

[Ref. 9017]

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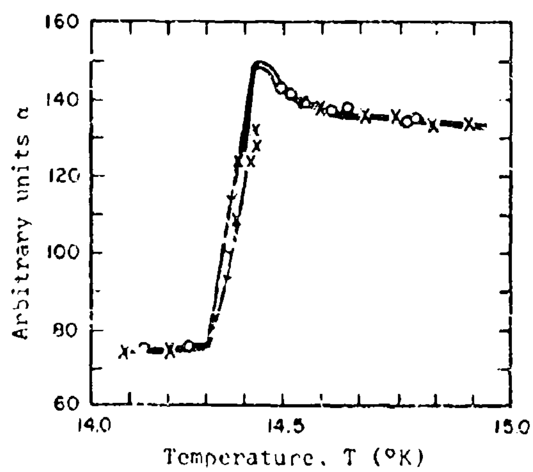
NIOBIUM-NITROGEN

TRANSITION TEMPERATURE

The samples in the following 2 graphs are prepared as follows:

Sample	Nitrogen at.%	N-Pressure atm.	Time Hours	Temperature °C
1	44.8	1.2	10	1450 - 1500
2	46.2	2	30	
3	48.3	9	50	
4	49.7	40	45	



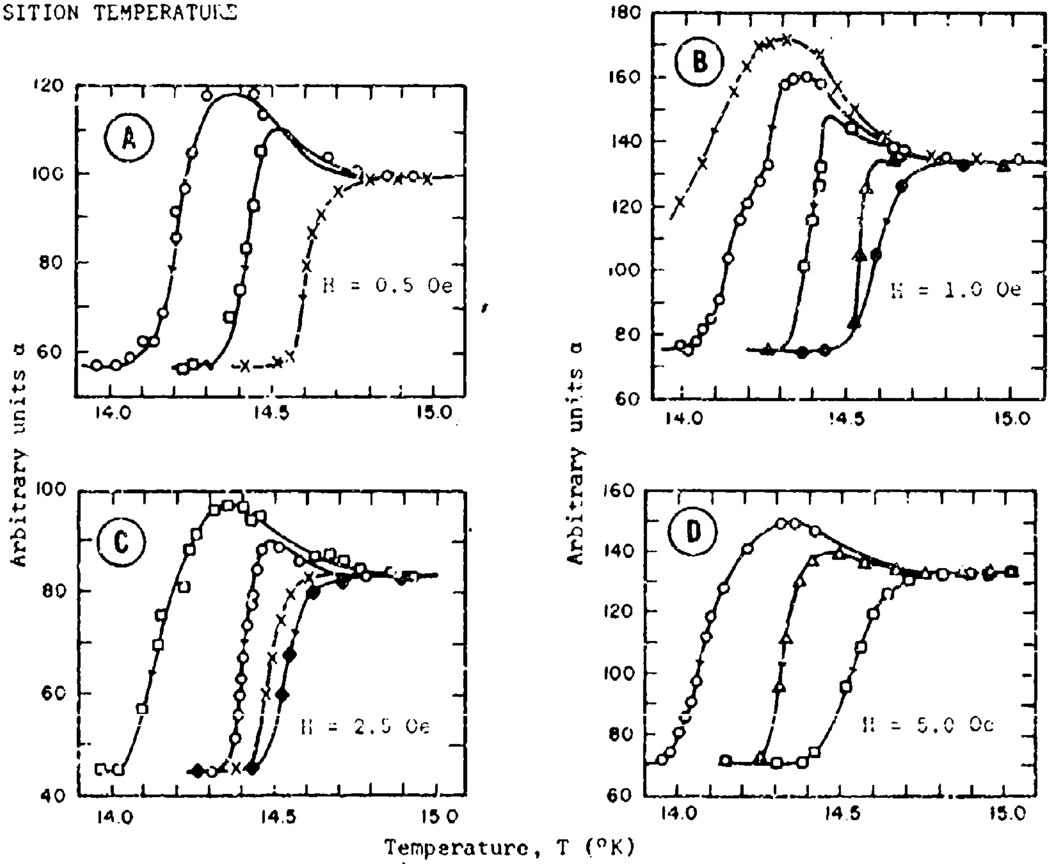
Transition curve for a niobium nitride sample. The results of measurement on the sample taken at various field and current conditions are shown in the following graph.

H = 1.0 Oe
I = 10 Amp

[Ref. 10720]

NIOBIUM-NITROGEN

TRANSITION TEMPERATURE



Transition curves for niobium nitride under various field and current conditions. Sample preparation: 40 atm. pressure N at 1450-1500 for 45 hours. 49.7 at.% present.

A J (Amp)		B J (Amp)		C J (Amp)		D J (Amp)	
×	0	●	0	◆	0	□	0
□	10	▲	5	×	5	Δ	10
○	15	□	10	○	10	○	15
		○	15	□	15		
		×	20				

[Ref. 10728]

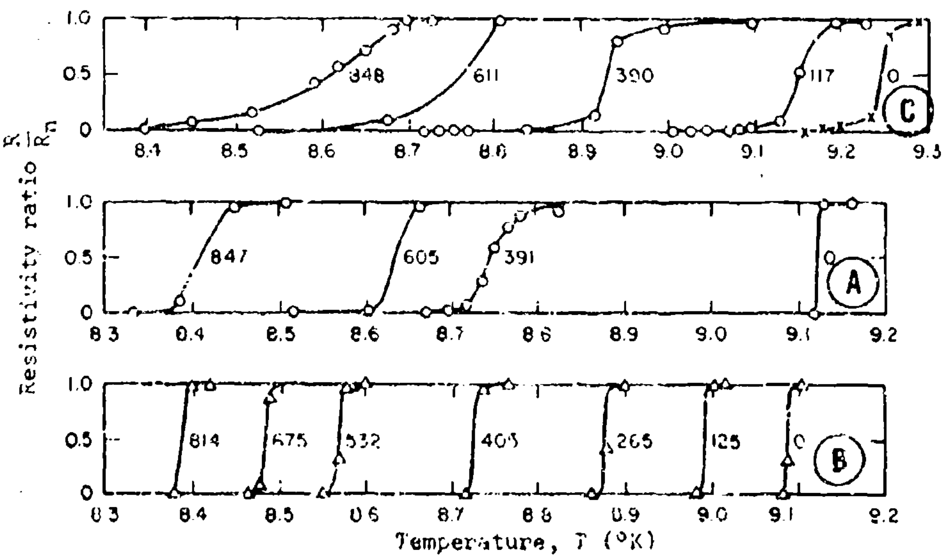
NIOBIUM-NITROGEN

TRANSITION TEMPERATURE

The specifications on the samples used in the following graph are given below:

0.029 inch diameter wire

Property	As Received	Annealed at 1875°C for 2 Hrs. in 3×10^{-6}mm Hg	Electron-beam Melted, 5 Passes
$\frac{R_{293°K}}{R_{10°K}}$	~110	~280	500
Tc	9.67	9.20	9.46



Transition curves for niobium-nitrogen systems at various field strengths. Field strength measured in Oe, is indicated on the curve. The data were taken at 7.2 A/cm^2.

A) .33 at.% N, He quenched

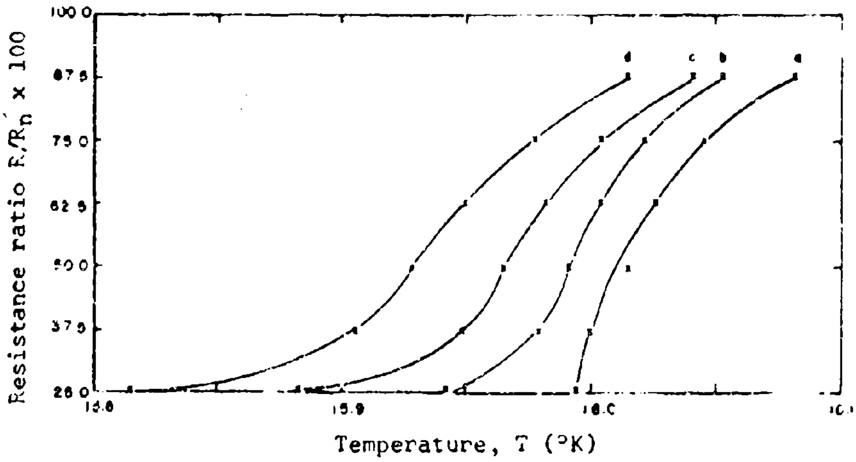
B) .33 at.% N, vacuum quenched

C) 1.64 at.% N, vacuum quenched

[Ref. 13360]

NIOBIUM-NITROGEN

TRANSITION TEMPERATURE



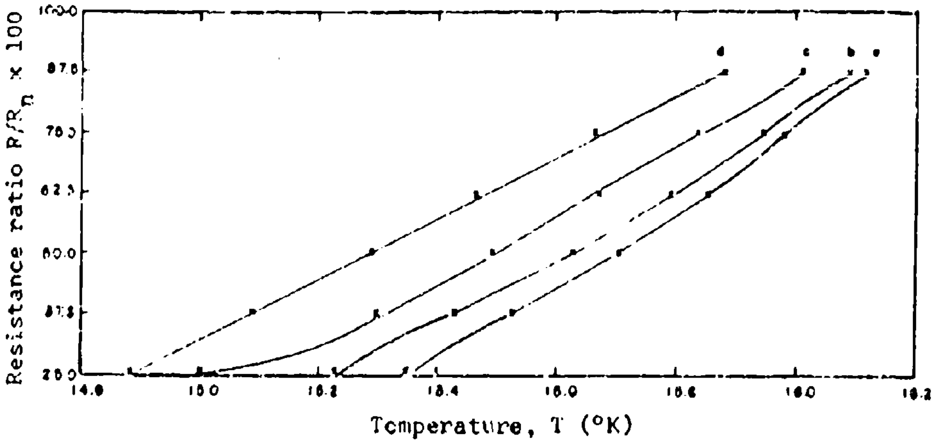
Current

a) 0.010 milliamp
b) 0.100
c) 0.501
d) 10.378

Transition curves for a NbN ribbon cut from a 1 mil sheet. R_{300} = 0.19Ω. The Nb was heated in ammonia at 1550°C for 90 minutes.*

Current

a) 0.025 milliamp
b) 0.100
c) 1.001
d) 9.936



Transition curves for a 5 mil NbN wire R_{300} = 0.2 . The Nb was heated in ammonium at 1225°C for 30 minutes.*

* Plotted by EPIC staff

[Ref. 10750]

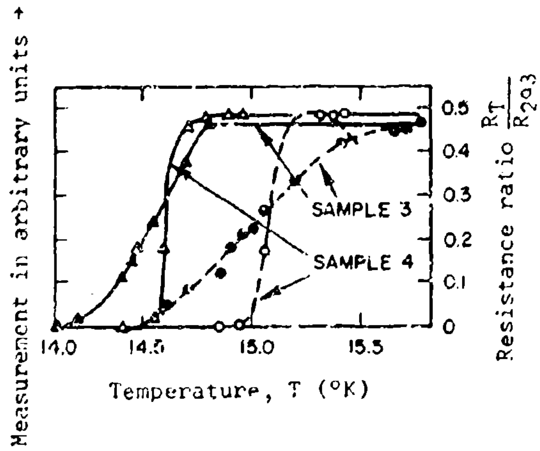
NIOBIUM-NITROGEN

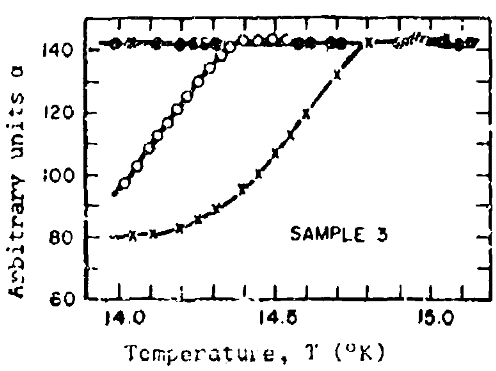
TRANSITION TEMPERATURE

Transition curves for niobium nitride samples.

H = 1 Oe

——— I = 0.017 Amp
- - - - - I = zero Amp





Transition curves for niobium nitride.

H = 1 Oe

x x x I = zero Amp
o o o I = 10 Amp
• • • I = 20 Amp

Sample	Nitrogen At.%	N-Pressure atm	Time Hours	Temperature °C
1	44.8	1.2	10	1450 - 1500
2	46.2	2	30	
3	43.3	9	50	
4	49.7	40	45	

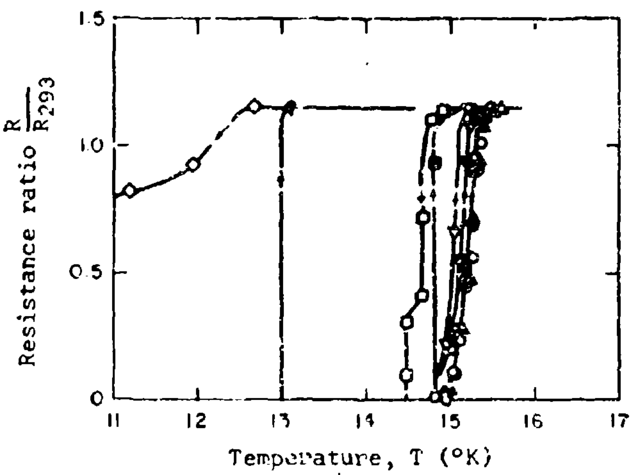
[Ref. 10728]

NIOBIUM-NITROGEN

TRANSITION TEMPERATURE

The effect of current on the transition curves of niobium nitride.

Current I (10^{-2} Amp)	Rising	Falling
.17	●	⊖ ○
1.7	▲	Δ
17.0	▼	∇
4.8	■	□
11.0	◆	◇



[Ref. 9617]

NIOBIUM-OXYGEN

TRANSITION TEMPERATURE

Lattice Constant and Transition Temperature

Wt.% O	At.% O	Lattice Constant (Å) a_o	Transition Temperature T_c (°K)	Notes	Ref.
0.101	-	3.3002 ± 0.0002	-	Oxygen absorbed for 2 hours at 1000°C.	21113
0.124	.70	-	8.78	Wires were drawn from electron-beam melted stock, then annealed & outgassed in high vacuum before dissolving oxygen into the sample.	13366
.26	1.4	-	5.840	-	15227
.27	1.52	-	8.04	-	13366
.32	1.80	-	7.80	-	"
.75	-	3.3112 ± 0.0002	-	Oxygen absorbed for 37 hours at 1050°C.	21113
.86	2.6	-	7.04	See note for 13366 above.	13366

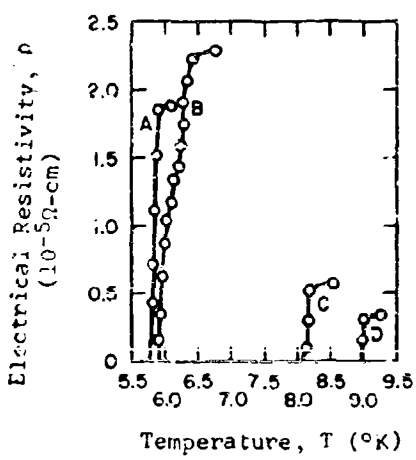
NIOBIUM-OXYGEN

TRANSITION TEMPERATURE

The specifications on the samples used in the following three graphs are given below:

0.029 Inch Diameter Wire

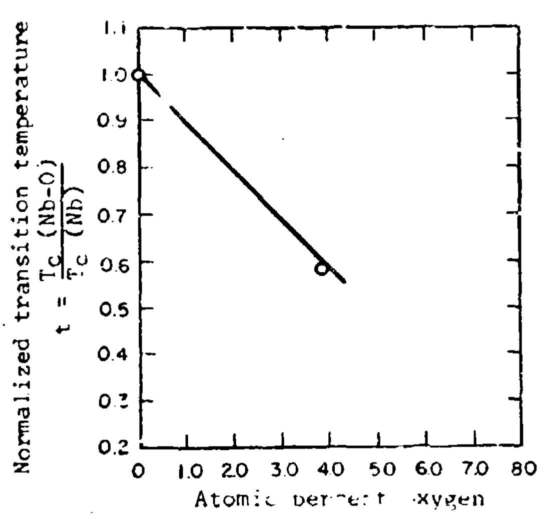
Property	As Received	Annealed at 1875°C for 2 Hrs. in 3 x 10^{-6}mm Hg	Electron-Beam Melted, 5 Passes
$\frac{R_{293°K}}{R_{10°K}}$	~110	~280	500
T_c	9.67	9.20	9.46



Electrical resistivity for niobium-oxygen systems. Current density J = 7.2 Amp/cm^2.

A) 3.83 at.% O
B) 5.18 at.% O
C) 1.43 at.% O
D) 6.43 at.% O

o = warming
x = cooling



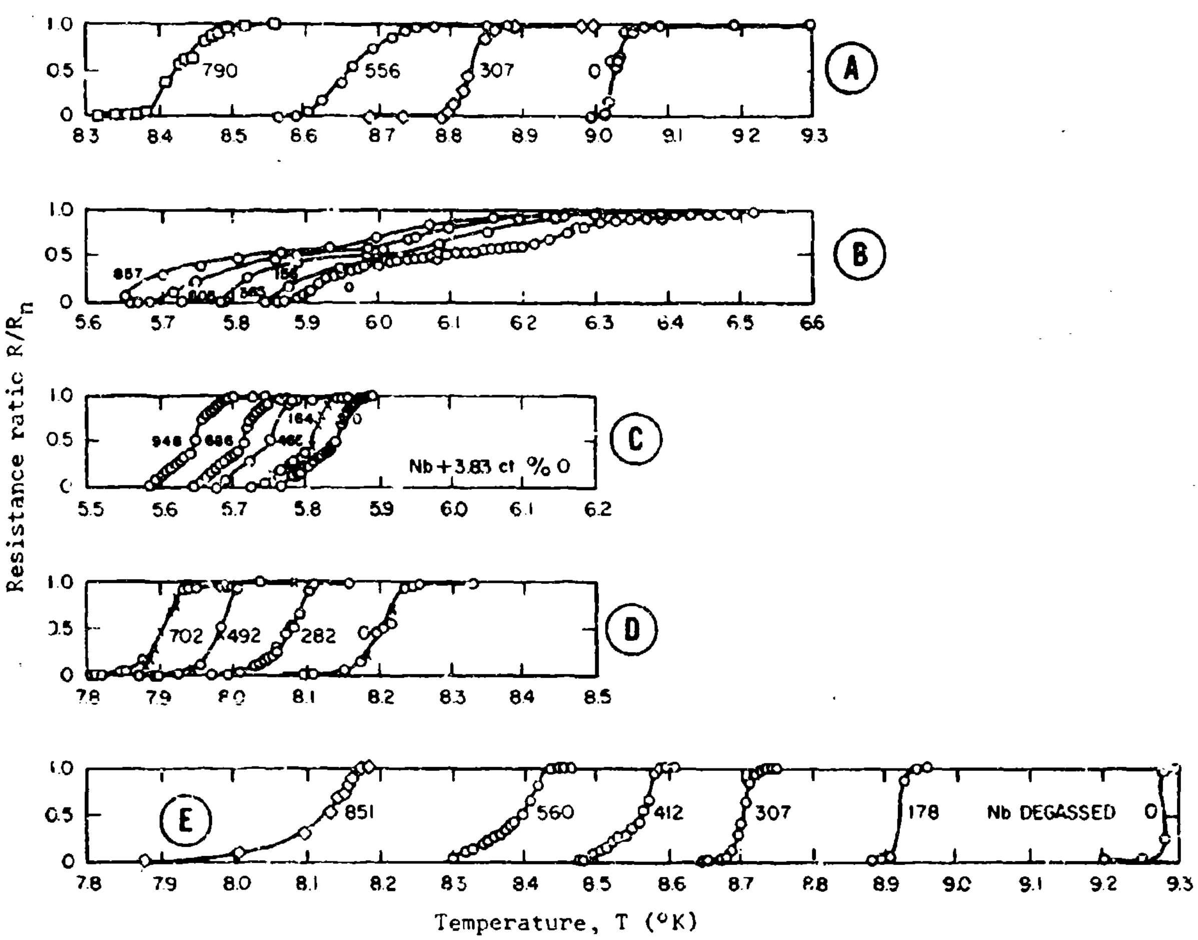
The normalized transition temperature as a function of composition for the Nb-O system.

$$\frac{d\ T_c}{d\ (at.\%\ O)} = -0.93(°K/at.\%)$$

[Ref. 13366]

NIOBIUM-OXYGEN

TRANSITION TEMPERATURE



Field effect on the transition curves of niobium-oxygen systems. Field strength measured in Oe, is indicated on the curves.

$J = 7.2$ Amp/cm^2

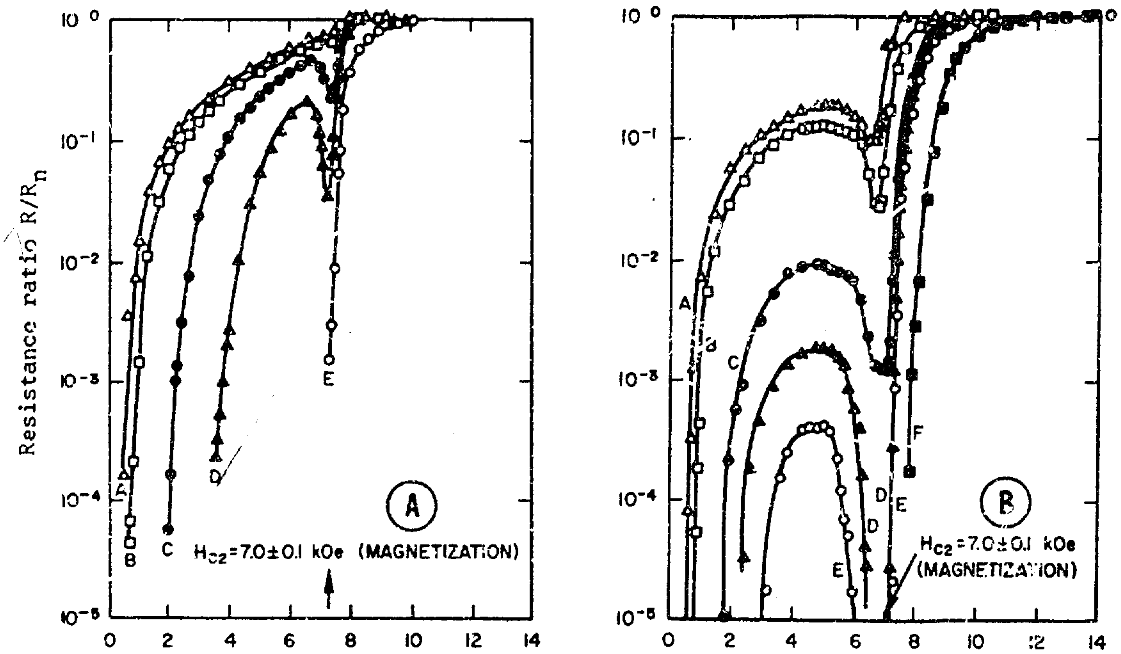
graph	at.% O
A)	6.43
B)	5.18
C)	3.83
D)	1.43
E)	0

o warming
x cooling

[Ref. 13366]

NIOBIUM OXYGEN

TRANSITION TEMPERATURE



Field strength, H (kOe)

The transition curves for niobium ribbon with 0.80 at.% oxygen at various current densities. H $\perp$ J and also perpendicular to the wide side of the ribbon. H_{c2} = 7.0 ± 0.1(kOe).

(A) annealed

	I(A)	J(A/cm²)
A)	0.90	865
B)	0.550	526
C)	0.230	220
D)	0.115	111
E)	0.010	9.6

(B) cold worked

	I(A)	J(A/cm²)
A)	4.75	3287
B)	2.90	2007
C)	1.25	865
D)	0.95	658
E)	0.16	111

[Ref. 15459]

NIOBIUM-NITROGEN

CRITICAL FIELD

The specifications on the samples used in the following table are given below:

0.029 Inch Diameter Wire

Property	As Received	Annealed at 1875°C for 2 Hrs. in 3 x 10⁻mm Hg	Electron-beam Melted, 5 Passes
$\frac{R_{293°K}}{R_{10°K}}$	~110	~280	500
T_c	9.67	9.20	9.46

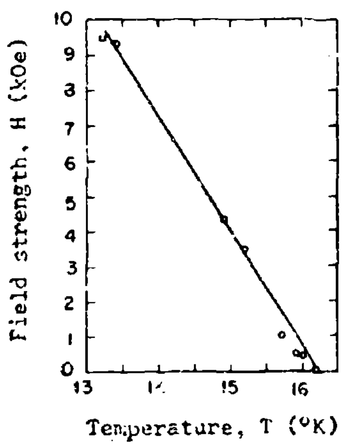
Critical Field

Material	T_c (°K)	ρ(μΩ-cm)	H_{cA}(Oe) (4.2°K)	$\left(\frac{\delta H_{cA}}{\delta T}\right)_{T_c}$	Hn (Oe) (4.2°K)	H_{fp} (Oe) (4.2°K)	Ref.
Nb	9.46	.035	1550	-403	2700	1320	13365
Nb + 0.23 at.% N	-	1.70	1480	-403	3000	780	"

H_{cA} is an approximation of H_c from the area under the magnetization curve.

H_{fp} is the field strength at first penetration.

H_n is the field strength when the sample is in the normal state.

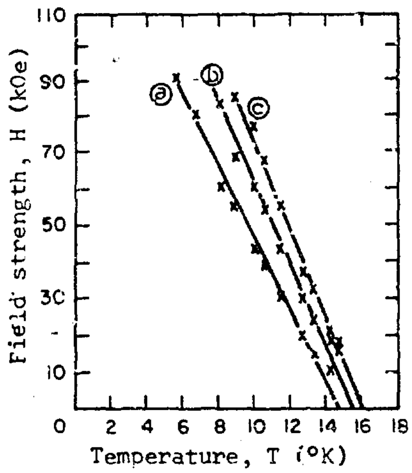


Critical field for niobium nitride (49.4 at.% N) as a function of temperature. Sample preparation: Nb powder was nitrided at 1 atm pressure of N for 3 hrs. at 1300°C.

[Ref. 18726]

NIOBIUM-NITROGEN

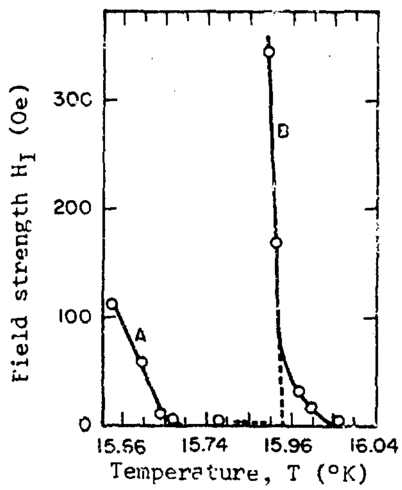
CRITICAL FIELD



Threshold field for niobium nitride (44.4 at.% N). Powdered Nb was pressed at 43,500 psi and heat-treated in a nitrogen stream for 24 hours at 1300°C and 24 hours at 1450°C.

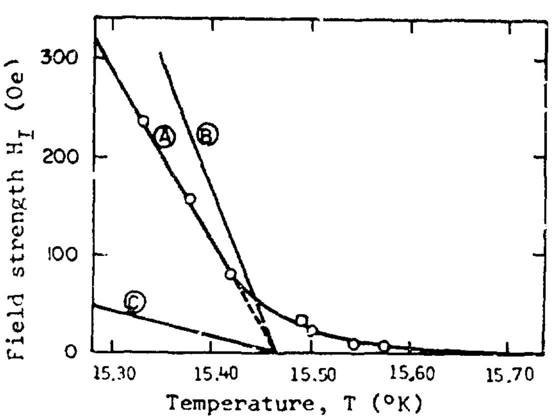
Sample	R/R_n
a	0.1
b	0.5
c	0.9

[Ref. 18457]



Critical field strength resulting from current densities in two NbN samples:

a) 1 mil ribbon, heated in ammonia at 1550° for 90 minutes.
b) 1/4 mil ribbon, heated in ammonia at 1350° for 30 minutes.



Critical field for 5-mil NbN wire. (R_n = 0.2Ω).

A) External field corresponding to a field from a current density which raises resistence to $5R_n$.
B) External field to raise resistence to $.5R_n$.
C) Calculated from (C_s-C_n) for a NbN powder. C_s is the heat capacity in the superconducting state. C_n is the heat capacity in the normal state.

[Ref. 10754]

NIOBIUM-OXYGEN

CRITICAL FIELD

Threshold Field

At.% O	Wt.% O	T_c (°K)	ρ (μΩ-cm)	H_{cA} (Oe) (4.20°K)		$\left(\frac{\partial H_{cA}}{\partial T}\right)_{T_c}$	H_n (Oe) (4.20°K)		H_{fp} (Oe) (4.20°K)	
0.70	0.124	8.78	3.9	1360	1425*	-403	7000	∿7550*	580	590*
1.52	0.27	8.04	8.2	1125	1260†	-403	∿9670	∿11600†	350	380†
1.80	0.32	7.80	9.6	1048	1210**	-403	∿10300	∿12600**	290	315**
2.60	0.46	7.04	13.7	840	1070††	-403	∿11500	∿15000††	170	200††

H_{cA} is an approximation of H_c from the area under the magnetization curve.

H_{fp} is the field strength at first penetration.

H_n is the field strength when the sample is in the normal state.

*3.85°K
†3.57°K
**3.40°K
††3.10°K

[Ref. 13366]

Residual Resistivity and Upper Critical Field

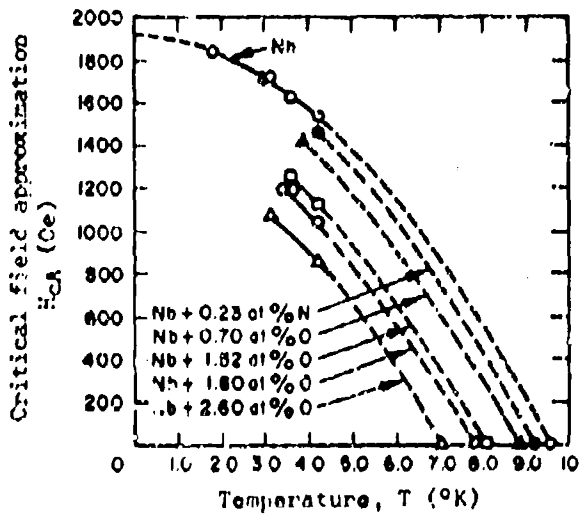
At.% O	Residual Resistivity (μΩ-cm)	Upper Critical Field H_{c2} (kGauss)
0.20	0.82	5.4
0.86	3.06	6.6
1.30	5.14	8.4

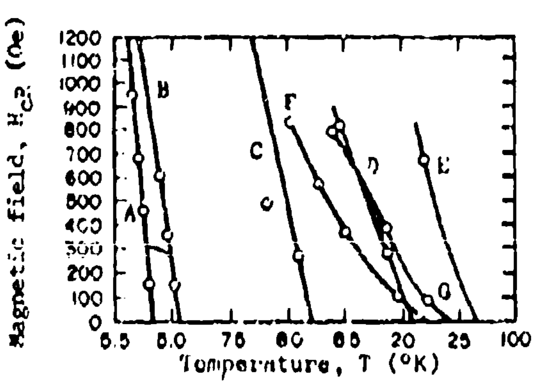
[Ref. 21039]

NIOBIUM-OXYGEN

CRITICAL FIELD

An approximation of the thermodynamic critical field H_c as a function of temperature. H_{cA} is approximated from the area under the magnetization curve, and $H_{cA} = H_0[1-(T/T_c)^2]$. [Ref. 13360]

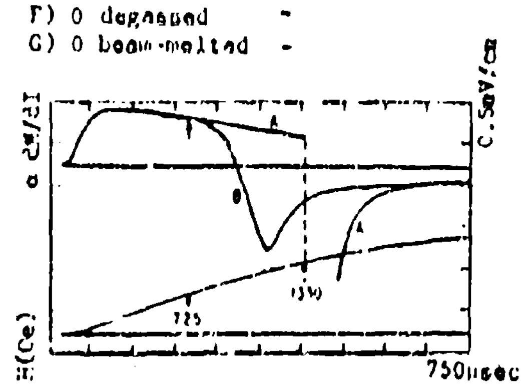




Critical field strength as a function of temperature for niobium-oxygen system. J = 7.2 Amp/cm². H_{cR} is the field at which R/R_n = .5 in the resistance ratio value. [Ref. 13366]

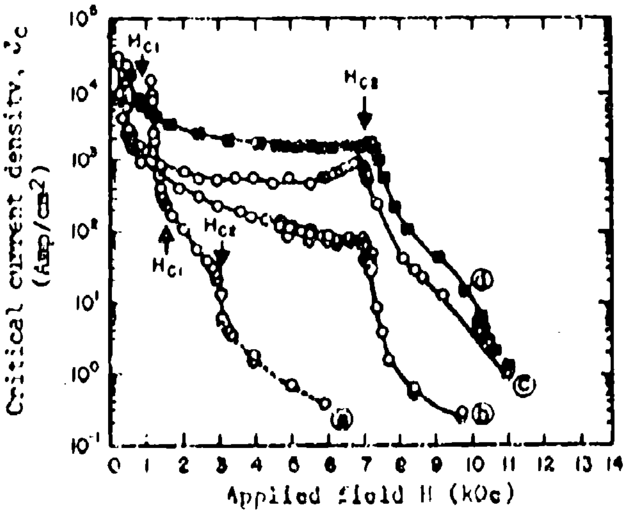
At.% O	$\left(\frac{\delta H_{cR}}{\delta T}\right)_{T \to T_c} \left(\frac{Oe}{°K}\right)$
A) 3.83	-5000
B) 3.18	-3400
C) 1.43	-1200
D) 0.43	-1250
E) 0	-1140
F) 0 degassed	-
G) 0 beam-melted	-

Oscilloscope traces showing initial penetration of the flux into an electropolished $Nb_{0.993}O_{0.007}$ wire. Trace A is for the sample in an optimum position and bottoms out near -18 mV. Trace B is for the sample moved 1.4 mm upward. Conventional tests show H_{c1} = 580 Oe, H_c = 1360 Oe, and H_{c2} = 7000 Oe. [Ref. 14582]



NIOBIUM-OXYGEN

CRITICAL CURRENT DENSITY



Critical current density for a Nb-O system (0.70 at.% O) as a function of applied field. H ⊥ J.

Wire (0.30 inches diam.)

a) Outgassed and annealed $\frac{R_{300°K}}{R_{10°K}} = 500$

b) Annealed

Ribbon (0.035 inches x 0.006 inches)

c) Cold worked H ⊥ w.s. (wide side)

d) Cold worked H ∥ w.s.

[Ref. 15459]

Critical current density for niobium with 0.86 at.% oxygen.

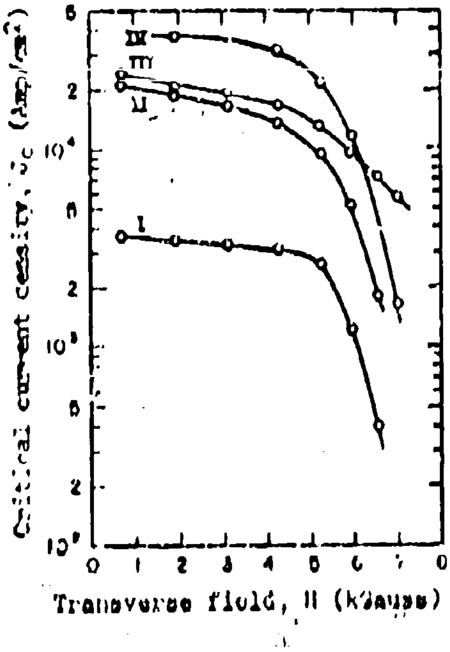
I. 0.8 mm diam. wire, soft annealed with oxygen atoms in random solution.

II. 0.3 mm diam. wire cold worked with oxygen atoms precipitated at dislocations.

III. 0.3 mm diam. wire cold worked with oxygen atoms in random solution.

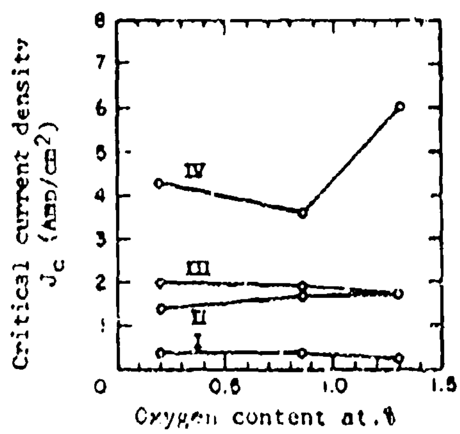
IV. 0.8 mm diam. wire soft annealed with partly ordered oxygen atoms.

[Ref. 21839]



NIOBIUM-OXYGEN

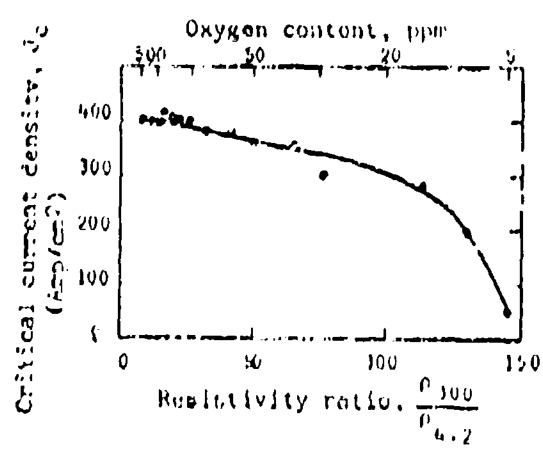
CRITICAL CURRENT DENSITY



Critical current density for Nb-O as a function of oxygen content. Data taken at 3(kGauss).

I. 0.8 mm diam. wire, soft annealed with oxygen atoms in random solution.
II. 0.3 mm diam. wire cold worked with oxygen atoms precipitated at dislocations.
III. 0.3 mm diam. wire cold worked with oxygen atoms in random solution.
IV. 0.8 mm diam. wire soft annealed with partly ordered oxygen atoms. [Ref. 21839]

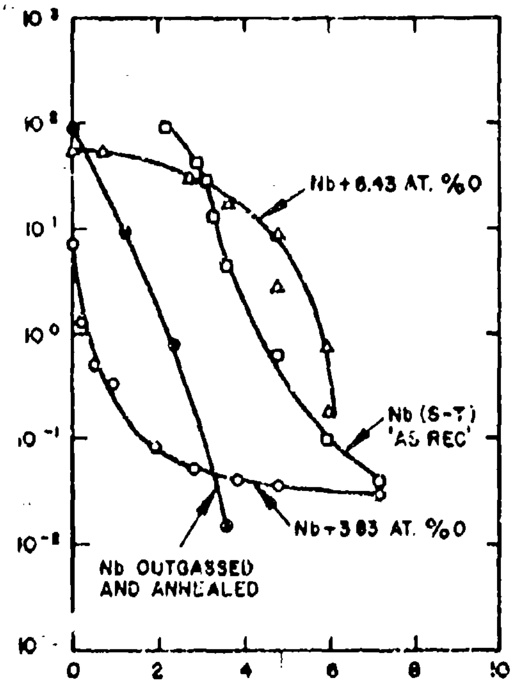
Effect of oxygen content on critical current density in single crystal niobium. The data were taken at 4.2°K and at the upper critical field H_{c2}.



[Ref. 19627]

NIOBIUM-OXYGEN

CRITICAL CURRENT DENSITY



Critical current as a function of transverse applied field. Data taken at 4.2°K.

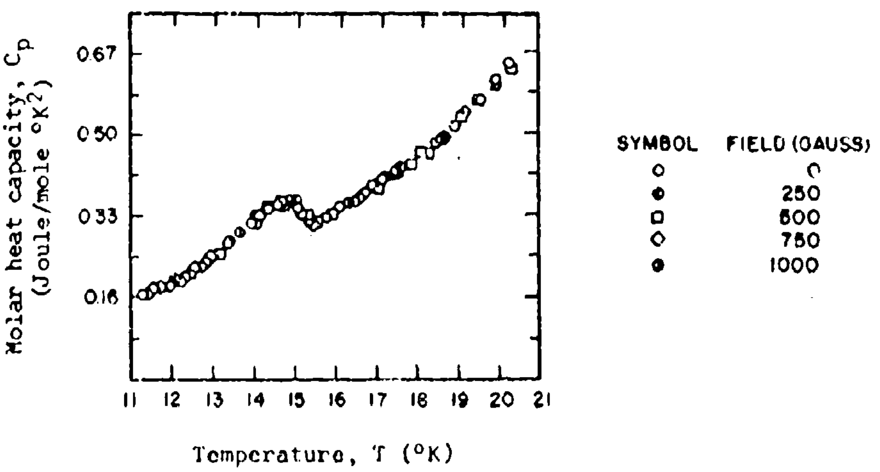
0.029 Inch Diameter Wire

Property	As Received	Annealed at 1875°C for 2 Hrs. in 3 x 10^{-6}mm Hg	Electron-Beam Melted, 5 passes
$\frac{R_{293°K}}{R_{10°K}}$	~110	~200	600
T_c	9.67	9.20	9.45

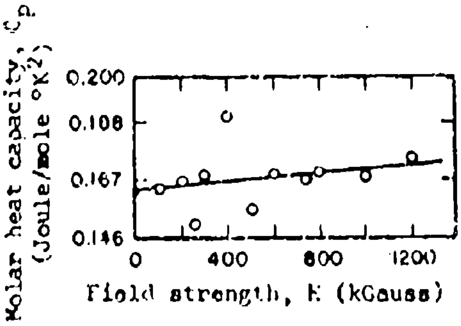
[Ref. 10366]

NIOBIUM-NITROGEN

SPECIFIC HEAT



Heat capacity as a function of temperature for NbN. The sample was prepared from powdered Nb heated in a nitrogen atmosphere for 12 hours at 1300°C.



Heat capacity as a function of field strength at 11°K. A powdered Nb sample was heated in nitrogen for 12 hours at 1300°C.

[Ref. 20629]

NIOBIUM-OXYGEN

SPECIFIC HEAT

Coefficient of Electronic Specific Heat

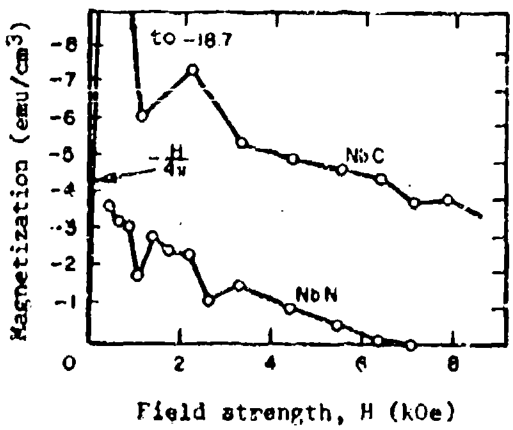
At.% O	γ (10^{-4} cal/mole °K^2) $\frac{V}{8\pi}\left(\frac{\delta H_{cA}}{\delta T}\right)^2_{T_c}$	$0.17\left(\frac{H_o^2}{T_c^2}\right)$
0.70	16.7	17.6
1.52	16.8	16.4
1.80	16.9	16.4
2.60	17.0	16.0

Data taken at 4.20°K

[Ref. 13366]

NIOBIUM-NITROGEN

MAGNETIC HYSTERESIS

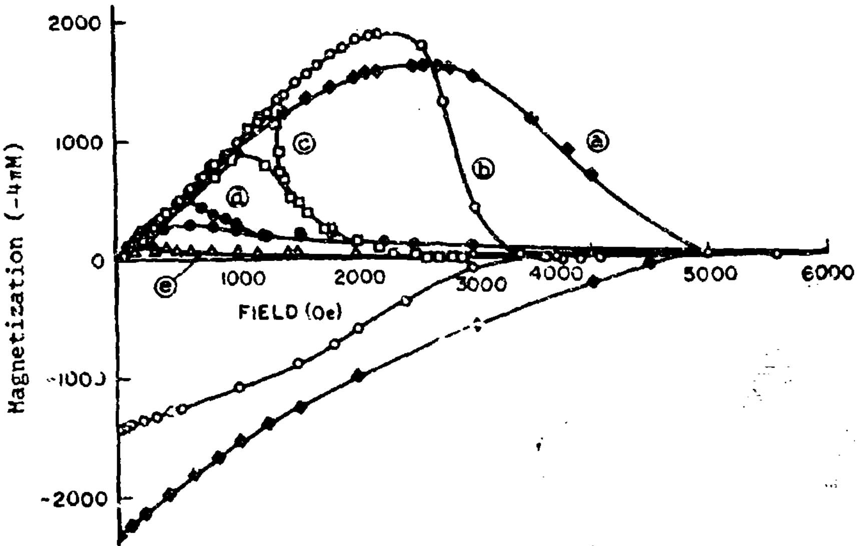


Magnetization for NbN as a function of applied field. Data taken at 4.2°K. NbC curve is shown for comparison.

[Ref. 21847]

NIOBIUM-OXYGEN

MAGNETIC HYSTERESIS

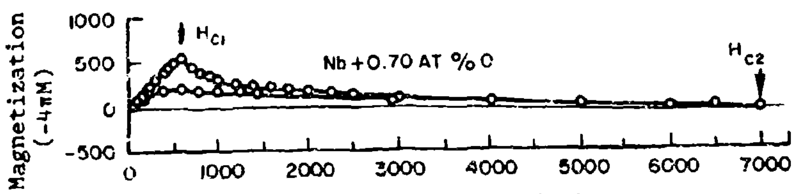


Field strength (Oe)

Magnetization as a function of field strength for the Nb-O system and Nb at 4.2°K.

a) Nb + 6.43 at.% O.
b) 0.020 inch diam wire, $\frac{R_{298^\circ K}}{R_{10^\circ K}} = 68$.
c) Sample referred to in table as annealed & outgassed.
d) Nb + 0.70 at.% O.
e) Nb + 1.75 at.% O.

[Ref. 13366]



Applied field, H (Oe)

Magnetization as a function of field strength for a Nb-O sample (0.70 at.% O) showing the upper and lower critical fields. Data taken at 4.2°K.

[Ref. 15459]

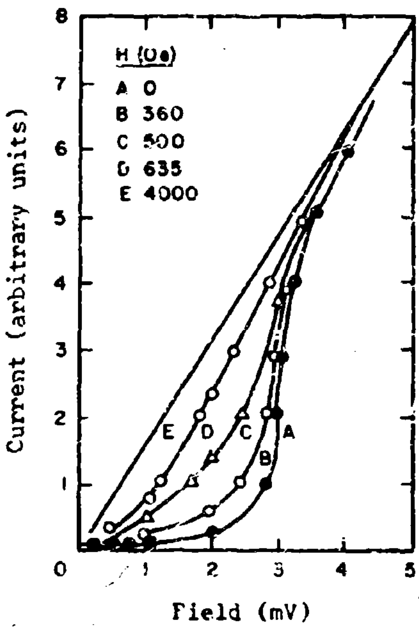
AIR FORCE MATERIALS LABORATORY
RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND

ELECTRONIC PROPERTIES INFORMATION CENTER

PREPARED BY ELECTRONIC PROPERTIES INFORMATION CENTER • HUGHES AIRCRAFT COMPANY, CULVER CITY, CALIFORNIA

NIOBIUM-OXYGEN

DEVICE



Tunnel current through a Nb-NbO-Pb sandwich at 4.18°K, at different magnetic fields. Zone refined Nb was outgassed at 2000°C and 20Å thick NbO films were formed by heating the Nb to 40°C in pure oxygen for 2 hours. Lead was deposited to 1000Å thickness. [Ref. 21733]

NIOBIUM-NITROGEN

SEMICONDUCTING PROPERTIES

Electrical Resistivity ρ (μΩ-cm)	Thermal Conductivity K(W/cm°K)	Seebeck Coefficient S(μV/°C)	Hall Coefficient R(10^{-4} cm³/coul)	Notes	Ref.
60	0.010	-	-0.13*	-	3803
200	-	-2.0	-	-	11599
-	-	-1.6	-	Arc melted	14991
-	-	+2.8	-	Annealed	"
200	0.033	-	-	-	13723
450	-	-	-	2050°C	18179

* $\delta = +0.22 \times 10^{-23}$ (cm/V²sec²)

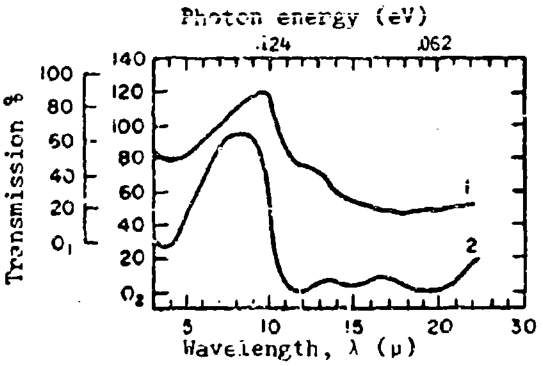
$$\delta = \frac{R}{e\rho^2} = n_e\mu_e^2 - n_h\mu_h^2$$

n is the carrier concentrations, μ is the mobility.

NIOBIUM-OXYGEN

ABSORPTION

1) Niobium was oxidized in a water solution of boric acid and borax, then the metallic niobium substrate was dissolved in hydrofluoric acid.
2) Monoclinc Nb_2O_5.



Absorption spectra for niobium oxide as a function of wavelength.

[Ref. 17133]

NIOBIUM-OXYGEN

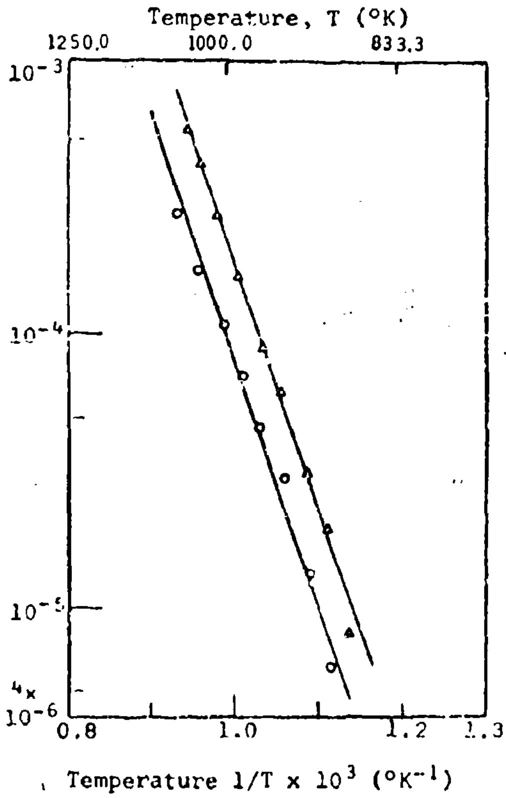
ELECTRICAL CONDUCTIVITY

Electrical conductivity for α-Nb_2O_5. Oxide powders were pressed at 40,000 psi and sintered 1300-1350°C for two hours. Measured in oxygen at:

Δ 0.12 atmospheres

o 0.9 atmospheres.

[Ref. 3274]

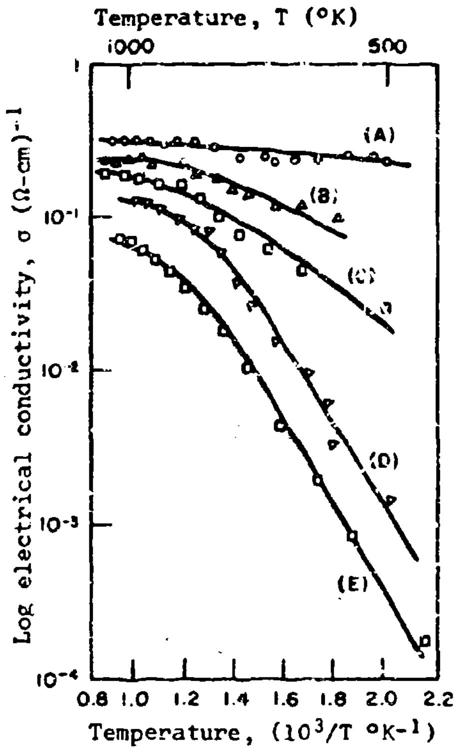


NIOBIUM-OXYGEN

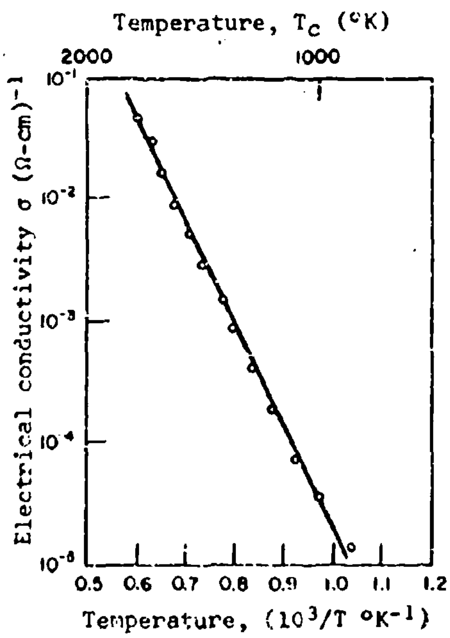
ELECTRICAL CONDUCTIVITY

Electrical conductivity of sintered α-Nb_2O_5 at 10^{-6} atm. pressure of air after reduction at the same pressure:

A) 8 hours at 875°C
B) 8 hours at 810°C
C) 1/2 hour at 860°C
D) 8 hours at 750°C
E) 1/2 hour at 800°C



[Ref. 5936]

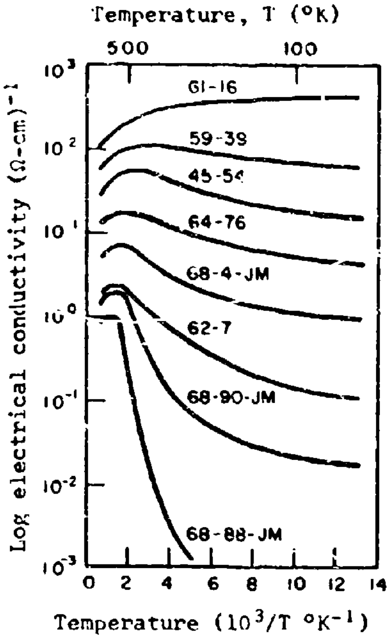


Electrical conductivity for near-stoichiometric α-Nb_2O_5 at 1 atm pressure oxygen. Powdered α-Nb_2O_5 was pressed at 15,000 psi and sintered at 1380°C.

[Ref. 7840]

NIOBIUM-OXYGEN

ELECTRICAL CONDUCTIVITY



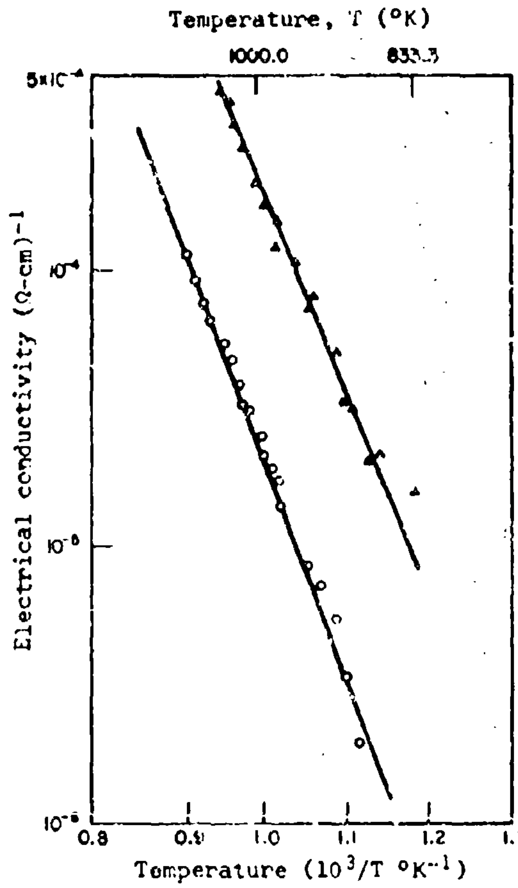
Electrical conductivity for non-stoichiometric α-Nb_2O_5. Nb_2O_5 powder was pressed to 20,000 psi and sintered in air at 1390°C for 3 hours, oxygen content and electron mobility at 1000°C are given below:

Sample designation	Nb_2O_x (X)	Electron mobility, μ (cm^2/V sec)
61-16	4.8632	0.211
59-39	4.9326	0.254
45-54	4.9558	0.194
64-76	4.9784	0.192
68-4-JM	4.9934	0.228
62-7	4.9980	0.284
68-90-JM	4.9980	0.221
68-88-JM	4.9988	0.231

[Ref. 4168]

NIOBIUM-OXYGEN

ELECTRICAL CONDUCTIVITY



Electrical conductivity for niobium oxide.

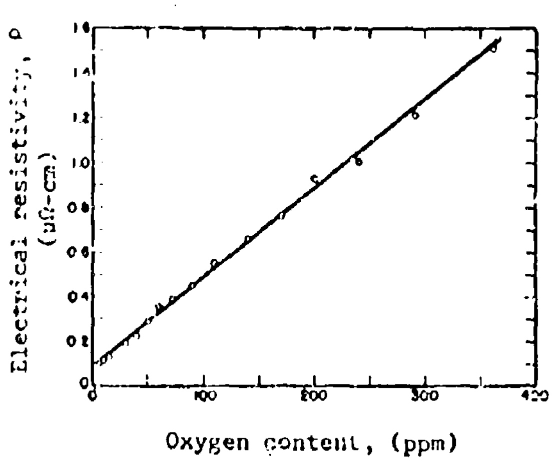
Δ α-Nb_2O_5 powder, pressed at 40,000 psi and sintered at 1300-1350°C for two hrs.

o Nb_2O_5 single crystal.

[Ref. 3274]

NIOBIUM-OXYGEN

ELECTRICAL RESISTIVITY

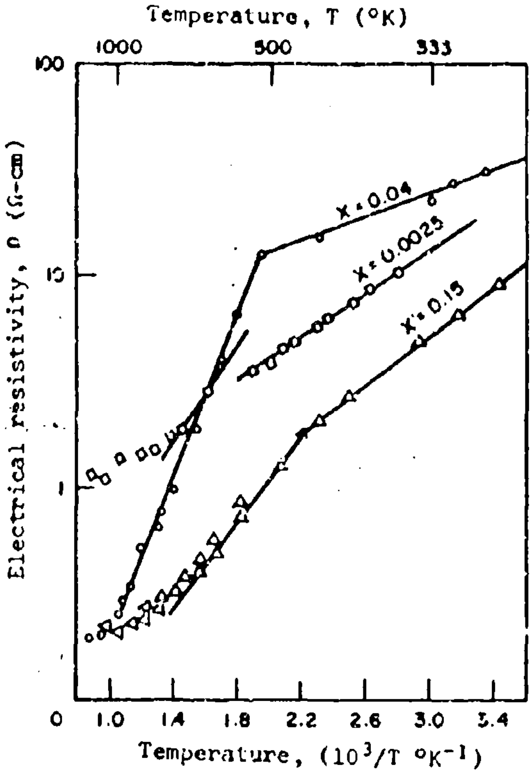


The effect of oxygen content on residual resistivity of niobium. Data taken at 4.2°K on single crystal niobium. After treatment, 5 ppm oxygen remained and the content shown in the graph was added.

[Ref. 19627]

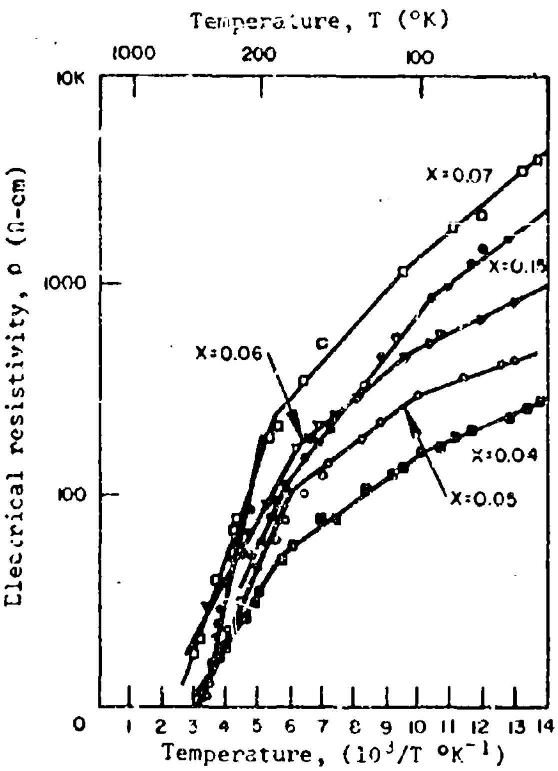
NIOBIUM-OXYGEN

ELECTRICAL RESISTIVITY



Electrical resistivity of sintered polycrystalline niobium oxide with varied tungsten content, $(Nb_{1-x}W_x)_2O_5$.

- o $(Nb_{.96}W_{.04})_2O_5$.
- □ $(Nb_{.9975}W_{.0025})_2O_5$.
- Δ $(Nb_{.85}W_{.15})_2O_5$.



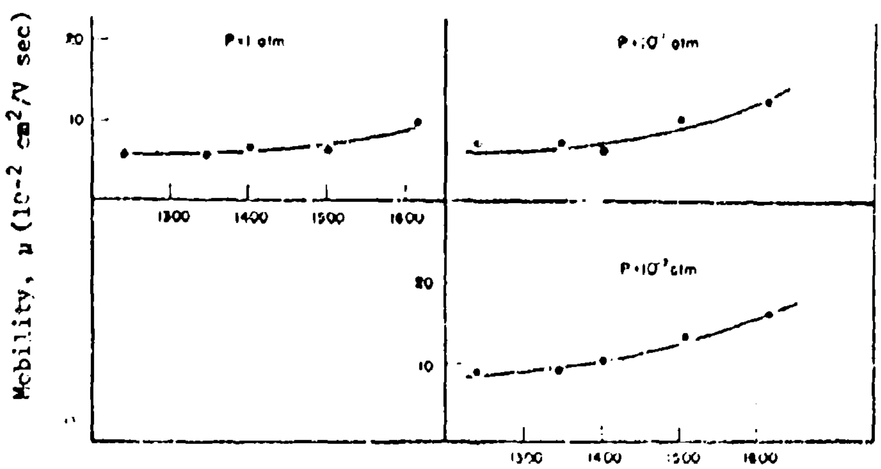
Electrical resistivity of sintered polycrystalline niobium oxide with varied tungsten content, $(Nb_{1-x}W_x)_2O_5$.

- □ $(Nb_{.93}W_{.07})_2O_5$.
- • $(Nb_{.85}W_{.15})_2O_5$.
- ∇ $(Nb_{.94}W_{.06})_2O_5$.
- o $(Nb_{.95}W_{.05})_2O_5$.
- ■ $(Nb_{.96}W_{.04})_2O_5$.

[Ref. 5956]

NIOBIUM-OXYGEN

MOBILITY



Electron mobility as a function of temperature for α-Nb_2O_5 at different oxygen vapor pressures.

[Ref. 16662]

Electron Mobility

Electron Mobility, (cm^2/V sec)	Sample	Temperature (°K)	Ref.
~.07	α-Nb_2O_5	1000	19883
0.218*	nonstoichiometric α-Nb_2O_5.	1273	14168

* This is an average of 24 values ranging from 0.09 to 0.40 as x (Nb_2O_x), increased from 4.8568 to 4.9992.

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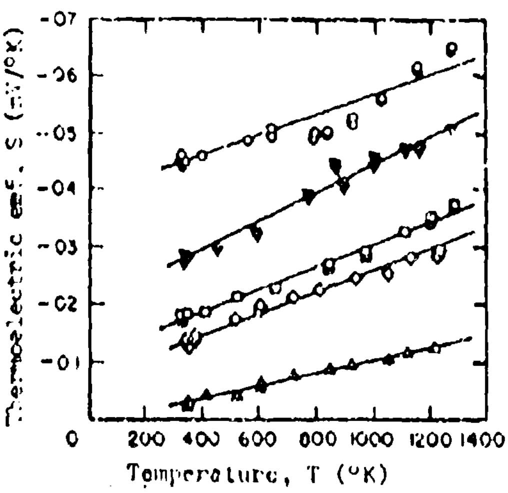
NIOBIUM-OXYGEN

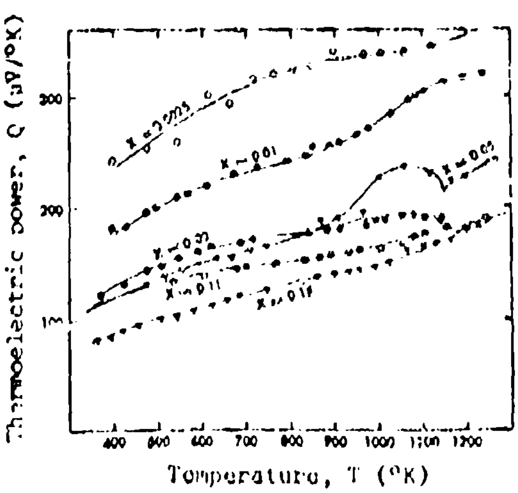
THERMOELECTRIC PROPERTIES

Temperature dependence of the Seebeck coefficient for nonstoichiometric α-Nb_2O_x. High purity oxide powder was pressed to 20,000 psi and sintered for 3 hours at 1300°C. Departures from stoichiometry were produced by isopiestic reduction and followed by homogenization at 1100°C for several days.

	Oxygen Content X
o	4.9988
▽	4.9977
▢	4.9908
◇	4.9814
△	4.8890



[Ref. 21734]



Thermoelectric power of sintered polycrystalline niobium oxide with varied tungsten content, $(Nb_{1-x}W_x)_2O_5$.

- o $(Nb_{.9975}W_{.0025})_2O_5$.
- ■ $(Nb_{.99}W_{.01})_2O_5$.
- ● $(Nb_{.97}W_{.03})_2O_5$.
- ▢ $(Nb_{.89}W_{.11})_2O_5$.
- ▼ $(Nb_{.85}W_{.15})_2O_5$.
- ▽ $(Nb_{.95}W_{.05})_2O_5$.

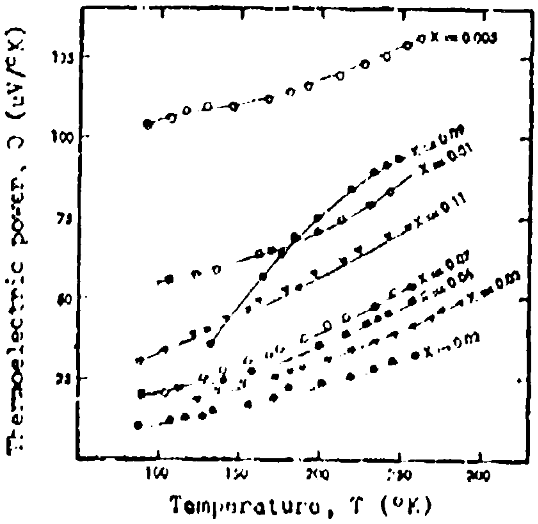
[Ref. 5956]

NIOBIUM-OXYGEN

THERMOELECTRIC PROPERTIES

Thermoelectric power of sintered polycrystalline niobium oxide with varied tungsten content, $(Nb_{1-x}W_x)_2O_5$.

- o $(Nb_{.995}W_{.005})_2O_5$.
- ● $(Nb_{.91}W_{.09})_2O_5$.
- □ $(Nb_{.99}W_{.01})_2O_5$.
- ▼ $(Nb_{.89}W_{.11})_2O_5$.
- o $(Nb_{.93}W_{.07})_2O_5$.
- ■ $(Nb_{.94}W_{.06})_2O_5$.
- ∇ $(Nb_{.97}W_{.03})_2O_5$.
- ● $(Nb_{.98}W_{.02})_2O_5$.



[Ref. 5956]

NIOBIUM-OXYGEN

DIELECTRIC PROPERTIES

The Nb_2O_5 samples in the two following graphs have the following impurities:

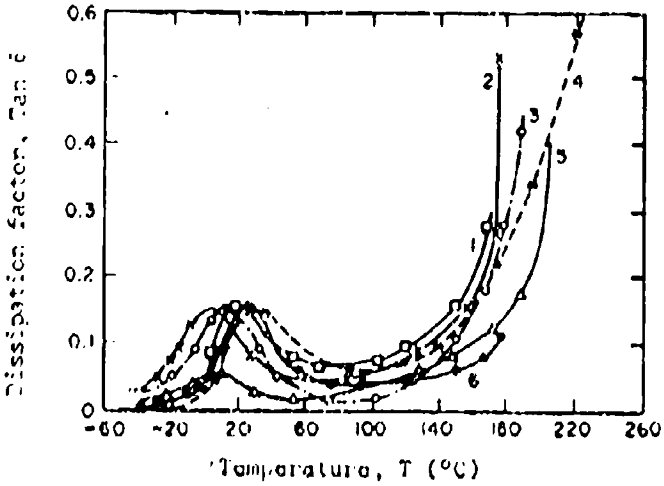
Wt.%

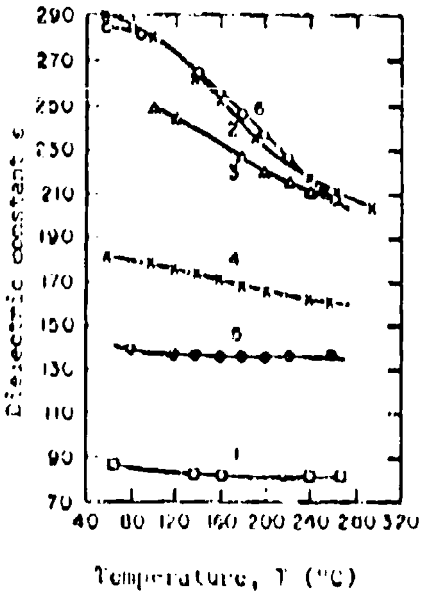
Sample #	SiO_2	TiO_2	Fe_2O_3	P_2O_5	SO_3	Ta_2O_5
1	0.01	0.17	0.04	-	-	-
2	0.02	0.24	0.01	<0.01	0.02	0.25
3	0.31	1.51	0.1	"	0.2	20
4	0.06	0.3	1.96	"	"	0.29
5	0.23	0.47	0.13	0.08	0.45	-
6	0.04	1.7	0.85	<0.01	0.02	0.6

NIOBIUM-OXYGEN

DIELECTRIC PROPERTIES

Temperature dependence of tan δ of Nb_2O_5. Sample preparation: Pressed powders were fired at 1350-1450°C. Measurements taken at 1 kc.



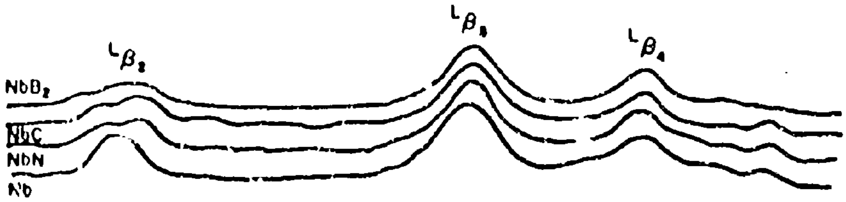


Temperature dependence of dielectric constant of Nb_2O_5. Sample preparation: Pressed powders were fired 1350-1450°C. Measurements taken at 1 Mc.

[Ref. 19117]

NIOBIUM-NITROGEN

PHOTON EMISSION PROPERTIES



The L series spectra for NbN. Curves are given for NbB_2, NbC and Nb for comparison.

[Ref. 16346]

L line intensities for Nb compounds:

Line	Nb	NbN	NbC	NbB_2
$L_{\alpha 1}$	100	100	100	100
$L_{\alpha 2}$	11	11	11	11
$L_{\beta 1}$	60.0	60.5	61.0	62.0
$L_{\beta 3}$	9.9	9.5	9.9	10.2
$L_{\beta 2}$	5.3	4.0	4.0	3.5
$L_{\gamma 1}$	2.0	1.47	1.48	1.40
N_{IV}	0.56	0.39	0.39	0.36
N_V	1.27	0.91	0.90	0.77
$N_{IV}+N_V$	1.83	1.30	1.29	1.13

Relative values of the variation of the $L_{\beta 2}$ and $L_{\gamma 1}$ lines for equal $L_{\beta 4}$ intensities.

Line	Nb	NbN	NbC	NbB_2
$L_{\beta 2}$	100	71.5	72.9	68.5
$L_{\gamma 1}$	37	26.3	27	27.6

[Ref. 15346]

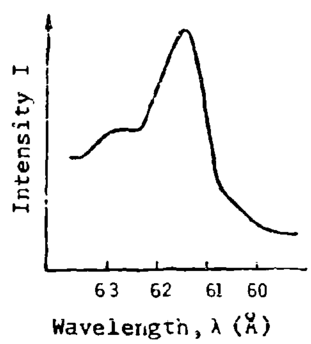
NIOBIUM-NITROGEN

PHOTON EMISSION PROPERTIES

Integral intensity of L_{β_2} bands for niobium nitrogen system, taking L_{β_2} line for Nb as unity.

At.% N	Integral Intensity
6.32	0.68
6.8	0.79
8.1	1 05
10.2	1.10
11.9	1.10
12.6	0.74

[Ref. 16347]



M emission band for Nb-N with 12.44% nitrogen.

[Ref. 19820]

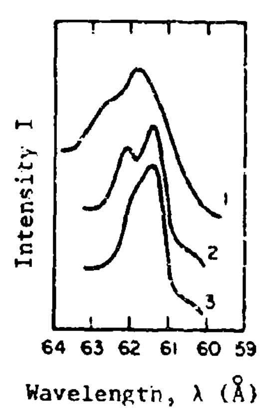
NIOBIUM-OXYGEN

PHOTON EMISSION PROPERTIES

M emission bands for:

1) Nb_2O_5
2) Nb (cold emitter)
3) Nb (above 100°C)

[Ref. 19820]



SECTION 2
NIOBIUM-NITROGEN-OXYGEN SYSTEMS

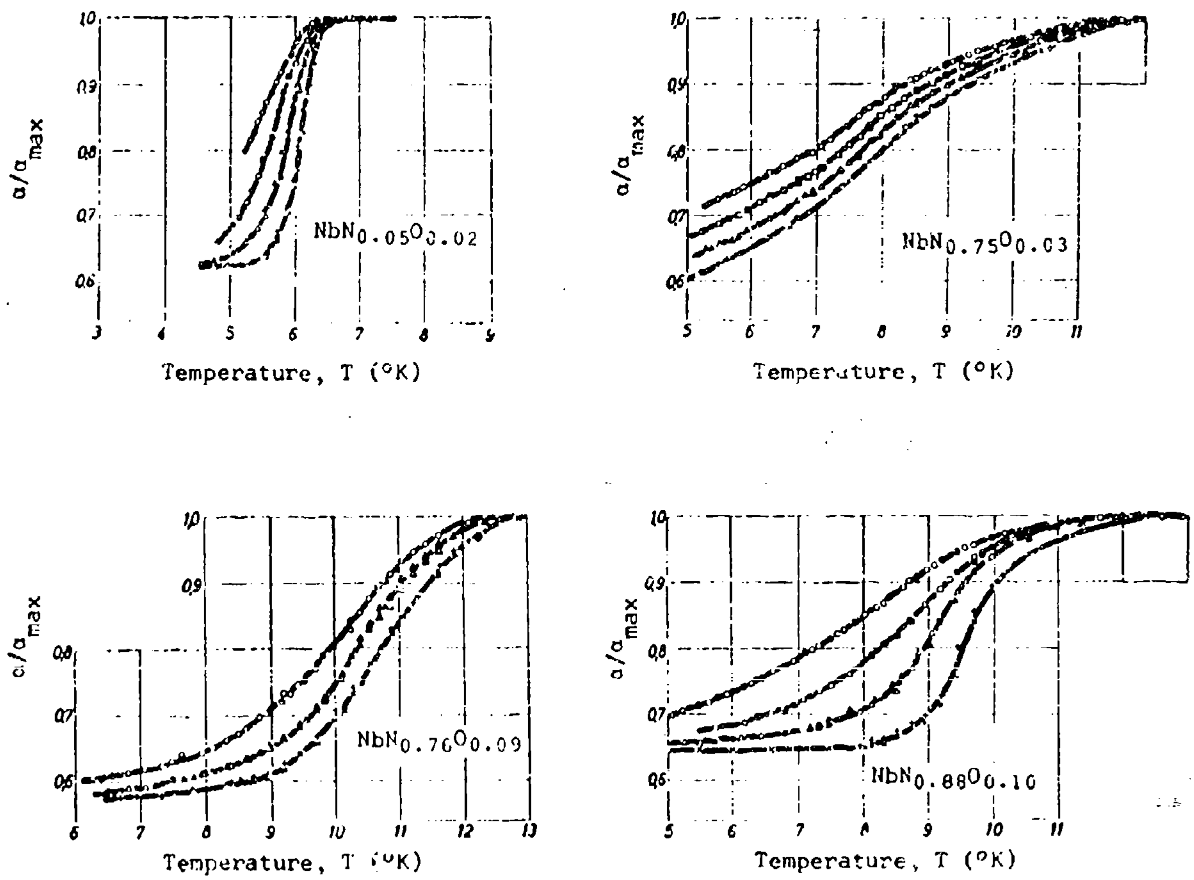
NIOBIUM-NITROGEN-OXYGEN

LATTICE CONSTANT AND TRANSITION TEMPERATURE

At.% N	Atomic Ratio N/Nb	O/Nb	Symmetry		Lattice Constant (Å) a_o	c_o	Transition Temp. °K Midpoint	Onset	Complete	Ref.
4.7	.05	.02	α	bcc	3.311	-	-	-	-	20714
"	"	"	"	"	-	-	5.28	6.5	4.9	9655
12.2	.14	.01	α+β	hcp	3.050	4.958	-	-	-	20714
"	"	.03		"	-	-	6.02	7.1	5.0	9655
27.5	.38	.07		hex	-	-	-	< 1.94	-	"
35.7	.58	.02		hcp	3.050	4.989	-	-	-	20714
"	"	"		tetr	-	-	-	6.0	-	9655
39.3	.65	.05	β		4.386	4.367	-	-	-	20714
39.7	.66	.10			-	-	6.80	11.6	-	9655
43.5	.77	.07			4.386	4.329	-	-	-	20714
"	"	"			-	-	9.92	12.7	6.0	9655
46.8	.88	.10	γ	fcc	4.388	-	-	-	-	20714
"	"	.08	"	"	-	-	7.66	12.1	6.0	9655

NIOBIUM-NITROGEN-OXYGEN

TRANSITION TEMPERATURE



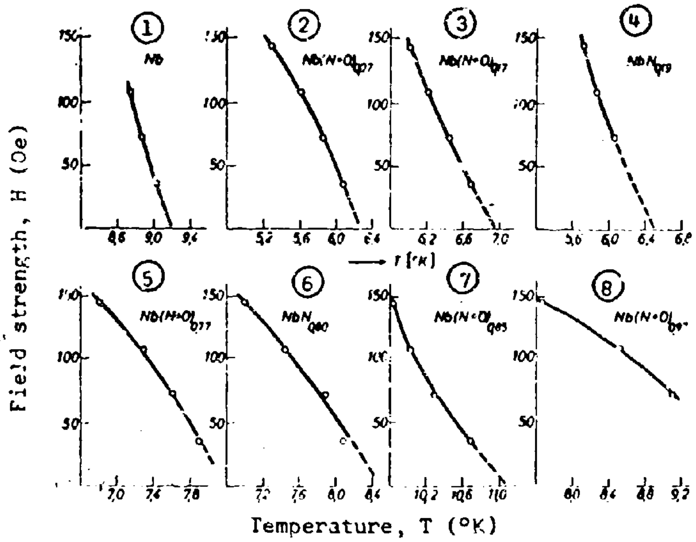
Transition curves for niobium nitride with residual oxygen.

Field (Oe)	Warming	Cooling
145	●	○
109	■	□
72.5	▲	Δ
36.2	+	x

[Ref. 9655]

NIOBIUM-NITROGEN-OXYGEN

CRITICAL FIELD



Critical field for niobium-nitrogen system with residual oxygen. Schröder's data on niobium nitrogen systems was supplemented by these data with residual oxygen. Some of the procedures used in the preparation of the NbN samples were eliminated and oxygen remained in the following amounts:

1) Nb
2) $NbN_{0.05}O_{0.02}$
3) $NbN_{0.14}O_{0.03}$
4) $NbN_{0.19}$
5) $NbN_{0.66}O_{0.10}$
6) $NbN_{0.80}$
7) $NbN_{0.77}O_{0.07}$
8) $NbN_{0.88}O_{0.08}$

[Ref. 9655]

SECTION 2
NIOBIUM-NITROGEN-M

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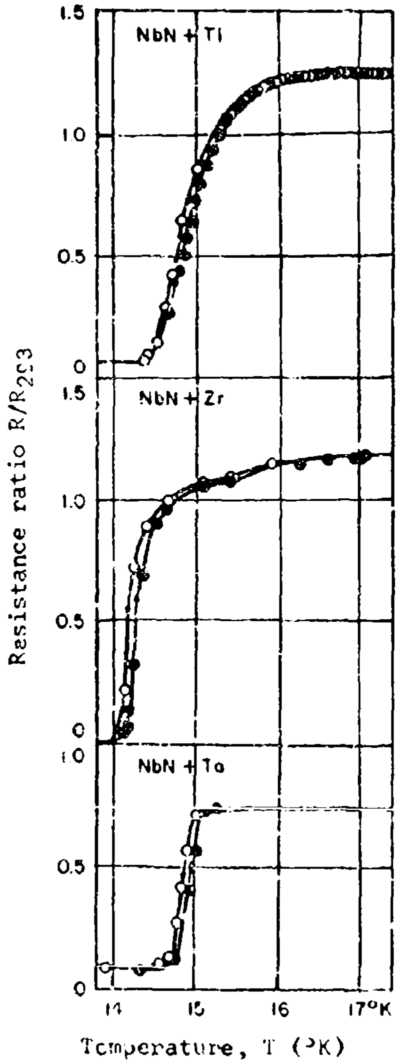
NIOBIUM-NITROGEN-M

TRANSITION TEMPERATURE



Transition curves for niobium-nitrogen system with additional metals. Strips of niobium 2mm × 0.06mm were alternated with 1-1.5mm × 0.35mm strips of the additional metal. These samples were rolled and heated 1 - 2 hours at 1700°C in vacuum. Then the diffused metal specimens were heated in nitrogen at 30-40 atmosphere of pressure for seven hours.

1) NbN + Ti
2) NbN + Zr
3) NbN + Ta

[Ref. 9617]

SECTION 3
NIOBIUM-MAGNESIUM & NIOBIUM-ALUMINUM SYSTEMS

NIOBIUM ALLOYS AND COMPOUNDS

NIOBIUM-MAGNESIUM AND NIOBIUM-ALUMINUM SYSTEMS

GENERAL

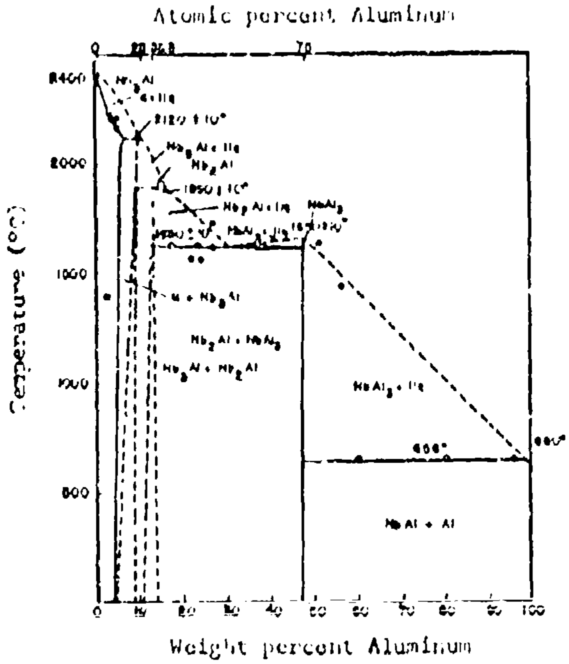
Nb-Al Three distinct compounds are formed in the niobium-aluminum binary system; Nb_3Al in the β-Wolfram phase, Nb_2Al in the σ-tetragonal and $NbAl_3$ in the tetragonal. The data available for these compounds include transition temperature, critical field, magnetic hysteresis, and magnetic susceptibility.

Lattice constants and transition temperatures are given for four ternary compounds; $Nb_3Al_{0.5}Ge_{0.5}$, $NbAl_xSb_{1-x}$, and $Nb_3Al_xSn_{1-x}$, with β-Wolfram structure and Nb_3Al_2C in the β-manganese. The nature of this latter structure is not fully understood and the lattice constants given for this material are those for the hexagonal subcell of the H phase. Johnston, et al, [Ref. 17803] claim that the β-manganese structure is favorable for the occurrence of superconductivity, however, in the niobium-aluminum system the β-tungsten structure gives better results.

Irradiation with fast neutrons 1.5×10^{18} n/cm^2, increases the critical current density, [Ref. 15568]. Primary flux 0.1-4.0 MeV. $\Delta J/nvt \left(\frac{10^5 A/cm^2}{10^{18} n/cm^2}\right) = 1.75$.

NIOBIUM ALUMINUM

GENERAL



Phase diagram for niobium-aluminum alloys. Powder samples, arc melted in He, 400-500 mm Hg pressure.

[Ref. 10280]

NIOBIUM-MAGNESIUM SYSTEM

TRANSITION TEMPERATURE

Nb-Mg The transition temperature for a niobium-magnesium sample, $NbMg_2$, is given as 5.6°K [Ref. 10784].

NIOBIUM-ALUMINUM

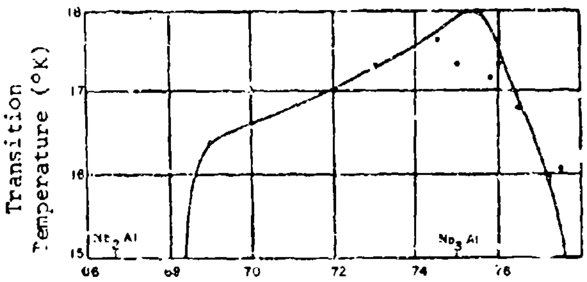
TRANSITION TEMPERATURE

Lattice Constant and Transition Temperature

At.% Al	Crystallography	Lattice Constant (Å) a_o	c_o	Nb-Al Transition Temperature T_c (°K)	Notes	Ref.
25	Nb_3Al, β-tungsten	5.187±.002			Pressed pellet fired in He arc furnace	14387
		--	--	16.8-18.0	--	9290
		--	--	17.0	--	13020
		--	--	17.1	Fired at 1500°C.	13155
		--	--	17.5	Fired at 1500°C.	"
		--	--	17.6	Melted granular compacts.	19482
		--	--	17.7	Arc-cast, before irradiation	15568
		--	--	17.48	Irradiated w/fast neutrons, 1.5 x 10^{18} n/cm^2, 0.1-4 MeV.	"
		5.183	--	15.7	--	19559
33	Nb_2Al, σ-tetragonal	9.957	5.167	--	--	14380
"	"	--	--	7-12	--	9290
75	$NbAl_3$, tetragonal	5.438	8.601	--	--	Hansen

NIOBIUM-ALUMINUM

TRANSITION TEMPERATURE

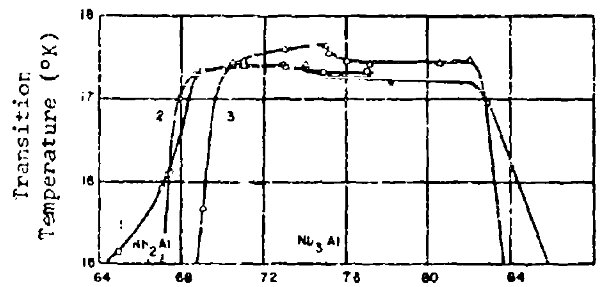


Transition temperature for a pressed, sintered, niobium-aluminum alloy as a function of niobium content. [Ref. 19482]

1 - pressed powder, presintered (1 hr. at 1000°C in vacuum)

2 - pressed powder, without presintering

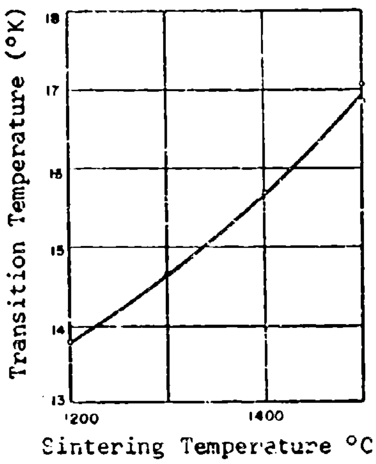
3 - compact granules, without presintering



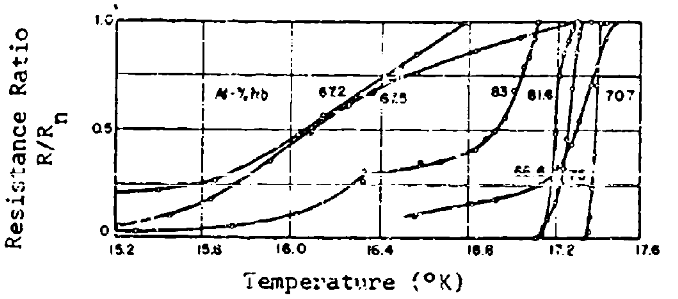
Transition temperature for niobium-aluminum alloys as a function of atomic percent niobium. Raetz and Saur claim a higher purity for the samples prepared from granules than those prepared from powders. Their sample preparations show a lower absorption of gases by the granules. [Ref. 19482]

NIOBIUM-ALUMINUM

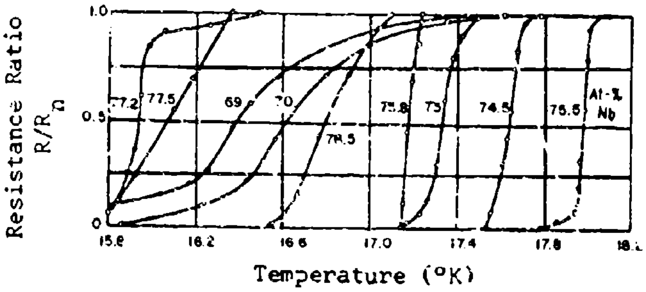
TRANSITION TEMPERATURE



Transition temperature as a function of sintering temperature for a pressed, sintered niobium-aluminum (Nb_3Al) powder. [Ref. 19482]



Transition curves for niobium-aluminum alloys. The niobium content (at.%) present in the alloy is indicated on the curve. Samples are arc-melted from a pressed powder without presintering.



Transition curves for niobium-aluminum alloys. The niobium content (at.%) in the alloy is indicated on the curve. Samples are sintered from a pressed powder.

[Ref. 19482]

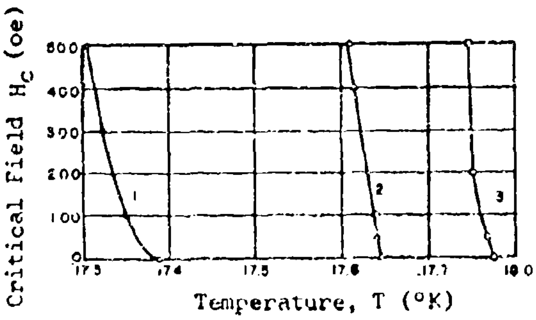
NIOBIUM-ALUMINUM

CRITICAL FIELD

1 - pressed powder without presintering (70.7 at.% Nb)

2 - compact granules without presintering (75 at.% Nb, Nb_3Al)

3 - pressed powder presintered 1 hr. at 1000°C in vacuum (75.5 at.% Nb, Nb_3Al)
For this sample $\frac{\delta H_c}{\delta T}$ = -40 kOe/°K

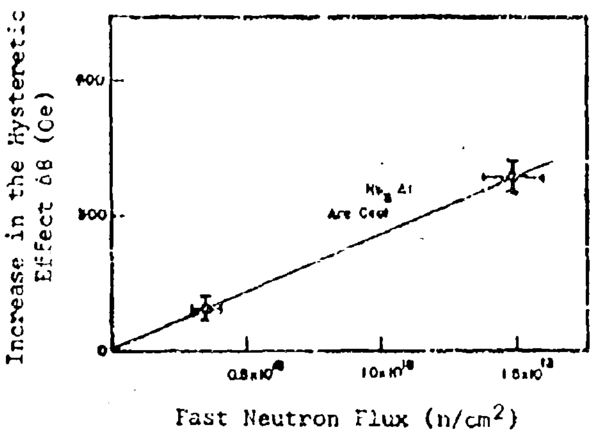


Critical field as a function of temperature for niobium-aluminum alloys. Samples were arc-melted. [Ref. 19482]

MAGNETIC HYSTERESIS

The change in magnetic hysteresis β as a result of fast neutron irradiation of a niobium-aluminum alloy. The sample was arc-cast from powder. Before irradiation, the magnetic hysteresis β of the sample, was equal to 60 Oe in a 4000 Oe field. Primary flux, 0.1-4 MeV.

[Ref. 15568]



neutron irradiation flux (n/cm²)	Applied Field (oe)		
	2000	3000	4000
5×10^{16}	187	123	89
3.5×10^{17}	311	205	147

Magnetic hysteresis for arc-cast Nb_3Al. Primary flux 0.1-4 MeV.

[Ref. 17820]

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NIOBIUM-ALUMINUM-M

TRANSITION TEMPERATURE

Lattice Constant and Transition Temperature

Formula	Crystal-lography	Lattice Constant (Å) a_o	c_o	Transition Temperature (°K)	Notes	Ref.
Nb_3Al_2C	β-manganese, H phase, hex subcell	2.07	8.02	< 4.2	Sintered and annealed at 1000°C in vacuum furnace, cooled	17803
$Nb_3Al_{.5}Ge_{.5}$	β-tungsten	5.175	--	17.6	Powder pressed & sintered 3 hours at 1500°C.	13155
$Nb_3Al_{.3}Sb_{.7}$	--	--	--	7.7	--	19559
$Nb_3Al_{<.3}Sb_{>.7}$	--	--	--	< 4.2	--	"
$Nb_3Al_xSn_{1-x}$	--	--	--	--	--	13155

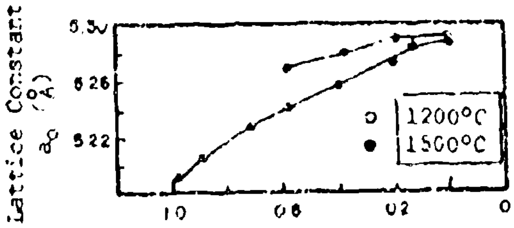
Aluminum content x	16 hours, 950°C a_o	T_c	$^*\Delta T_c$	16 hours, 1200°C a_o	T_c	ΔT_c	3 hours, 1500°C a_o	T_c	ΔT_c
0	--	17.9	0.5	5.292	18.1	0.2	--	--	--
.02	--	17.8	0.4	--	17.9	0.4	--	--	--
.04	--	19.0	0.2	--	18.0	0.2	--	--	--
.06	--	17.8	0.2	--	18.0	0.2	--	--	--
.08	--	--	--	--	17.9	0.2	--	--	--
.10	--	--	--	†5.290	18.4	0.06	†5.286	18.3	0.3††
							**5.281	16.2	1.3
.12	--	17.8	0.3	--	†19.4	0.3	--	--	--
.20	--	--	--	†5.290	16.9	0.7	5.272	13.1	2.9
.40	--	--	--	†5.278	15.4	0.4	5.257	15.1	0.9
.60	--	--	--	†5.270	15.2	0.6	5.238	14.5	2.8
.80	--	--	--	†5.262	14.6	0.4	5.217	15.6	1.0
.99	--	--	--	--	--	--	†5.200	16.1	1.0
1.00	--	--	--	--	--	--	5.186	17.1	0.8

$^*\Delta T_c$ is the width of the transition region. All powdered samples pressed and sintered except as follows: † not pressed before sintering, ** sintered sample was refired.

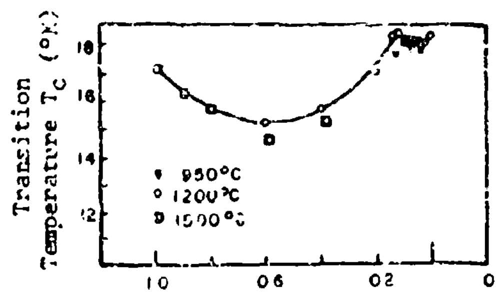
†† a sample with x = .10, fired for 3 hours at 1800°C without pressing had the following values: a_o = 5.276Å, T_c = 7.3°K, ΔT_c = 2.6

NIOBIUM-ALUMINUM-M

TRANSITION TEMPERATURE



Lattice constants as a function of composition for $Nb_3Al_xSn_{1-x}$.

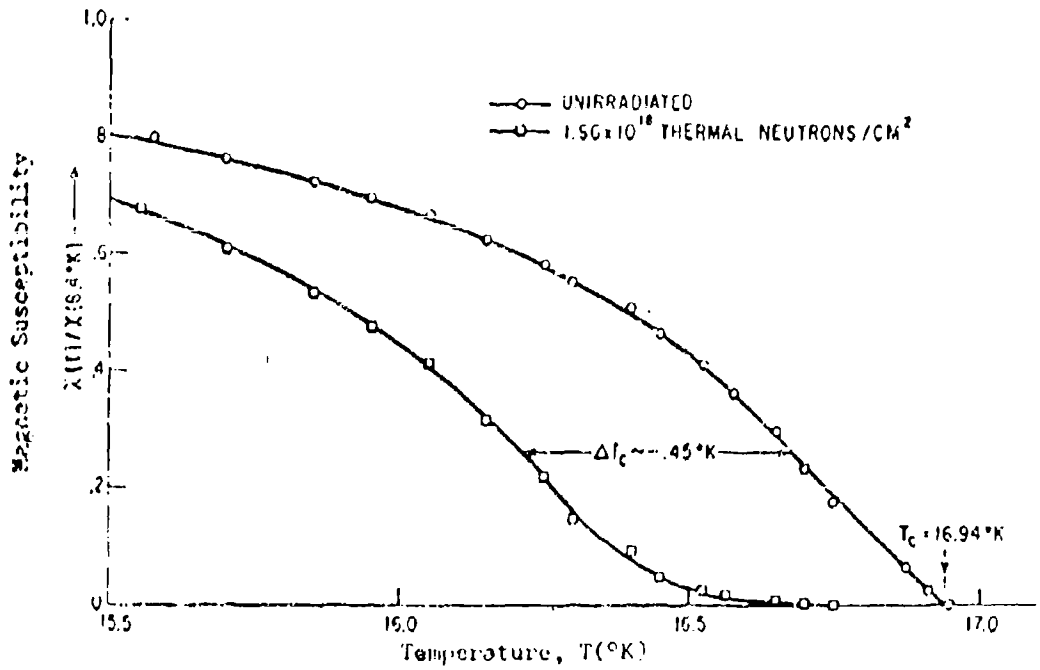


Transition temperature of a niobium-aluminum-tin alloy as a function of x in $Nb_3Al_xSn_{1-x}$.

Samples were pressed and sintered at temperatures indicated.

[Ref. 13155]

MAGNETIC SUSCEPTIBILITY

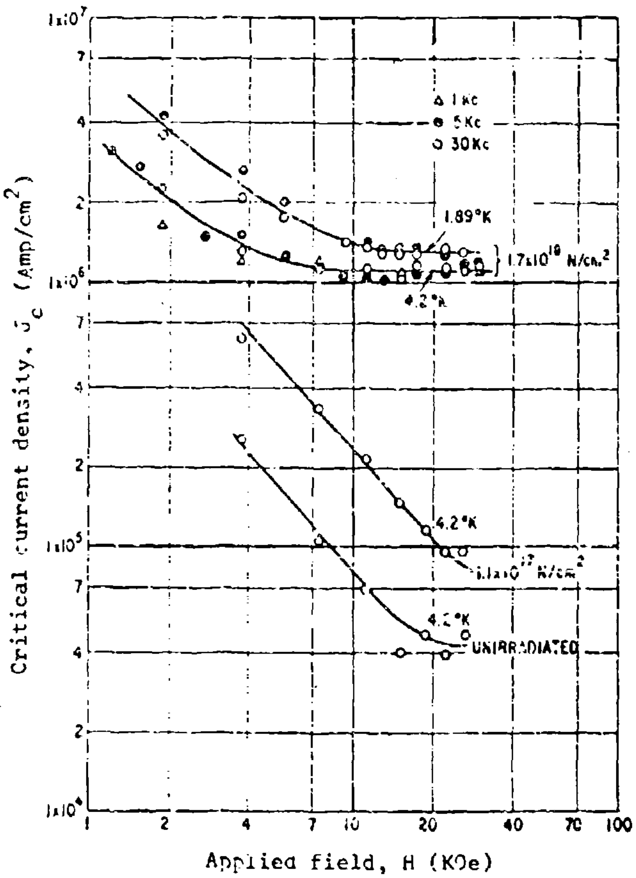


Normalized susceptibility for Nb3Al with .321 at.% U. The powdered samples were ground from an arc-cast rod.

[Ref. 21907]

NIOBIUM-ALUMINUM-M

CURRENT DENSITY



Current density of Nb_3Al as a function of applied field. The powdered samples, (70μ particles) were ground from arc cast ingots and irradiated by thermal neutrons. The samples contained .321 at.% U.

[Ref. 21908]

SECTION 3
NIOBIUM-SILICON & NIOBIUM-PHOSPHOROUS SYSTEMS

NIOBIUM ALLOYS AND COMPOUNDS

NIOBIUM-SILICON AND NIOBIUM-PHOSPHOROUS SYSTEMS

GENERAL

Nb-Si Until recently none of the niobium silicides showed a transition temperature above 1.20K†. The 1963 paper of Galasso and Pyle [Ref. 21256] reports a Nb_3Si compound, with an ordered Cu_3Au structure, to have a T_c of 1.5°K.

In a 1964 paper, Gold presented an empirical method of predicting the transition temperature of superconducting alloys and compounds. He claims that if Nb_3Si were to assume a β-tungsten structure, it would have a transition temperature between 22.6 and 30.9°K.*

One attempt to form niobium and silicon into the β-tungsten structure was made by Holleck, et al. They began with β-tungsten Nb_3Sn and added niobium and silicon in a 3:1 ratio. The samples were hot pressed and sintered for 50 hours at 1600°C. For compositions to 50 mole percent Nb(3)Si, the Nb_3Sn-Nb(3)Si system was homogeneous. The lattice constant at the 50 percent point was 5.25 Å. Projected to a possible β-tungsten structure, Holleck et al. claim the lattice constant for Nb_3Si to be 5.19 Å. There is further doubt about the existence of this phase since the Nb_5Si_3 phase will suppress the β-tungsten structure [Ref. 21457].

Nb-P No transition temperatures are reported for the niobium-phosphorous system. However, electrical resistivity data are given.

† The 1.20°K values come from [Refs. 9695 and 9793]. [Ref. 12215] gives the lowest temperature measured: T_c = 1.02°K.

* Gold, L., PHYS. STAT. SOL., v.4, p. 261 (1

NIOBIUM-SILICON

GENERAL

Lattice Constant

At.% Si	Formula	Crystallography		Lattice Constant (Å) a_o	c_o	Ref.
25	Nb_3Si	cubic:	Cu_3Au	4.211†	--	21256
37.5	Nb_5Si_3		$D8_8$	7.536	5.248	*
"	α-Nb_5Si_3	tetr:	Cr_5B_3 type	6.570	11.884	21416
"	β-Nb_5Si_3	tetr:	Ni_3P type	10.018	5.077	"
67	$NbSi_2$		C40	4.785 ± .005	6.576 ± .005	"

* Schachner, H., et al. MH. CHEM., v. 85, no. 1, p. 245 (1954).

† a_0 = 4.207 HCl transport method of preparation [Ref. 21843].

NIOBIUM-PHOSPHOROUS

GENERAL

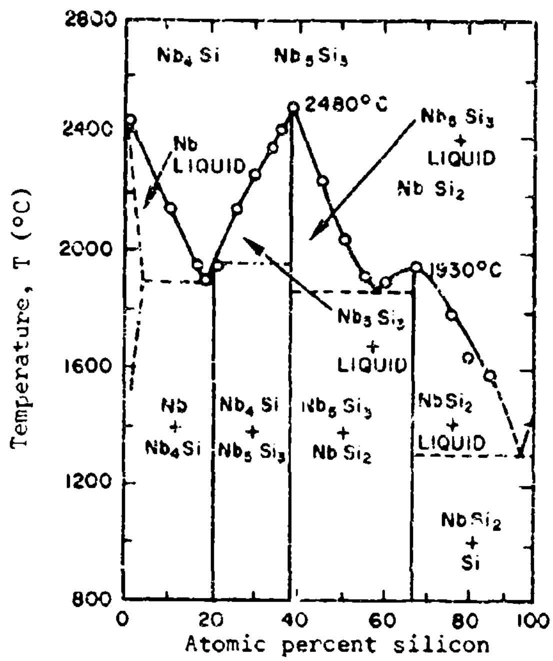
Lattice Constant

Compound	Lattice Constants (Å) a_o	b_o	c_o	β	Symmetry	Ref.
NbP	3.334	-	11.378	-	tetr.	*
NbP_2	8.878	3.266	7.529	119°8'±5'	monoclinic	20108

* Boller, H. and E. Partne. ACTA.CRYST., v. 16, p. 1095, (1963).

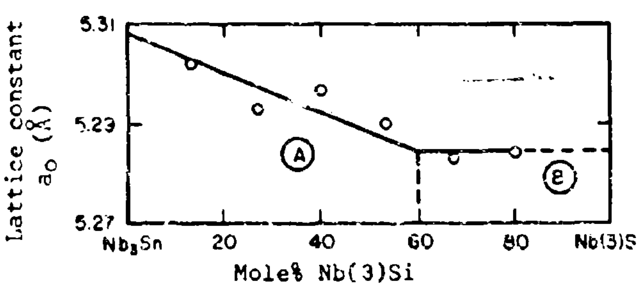
NIOBIUM-SILICON

GENERAL



Phase diagram for the niobium-silicon system. ○ observed melting points.

[Ref. 21421]



A - single phase region

B - two phase region

Lattice constant for the Nb_3Sn-Nb(3)Si system. At 50% Nb(3)Si a_o = 5.25 Å and the probable lattice constant for a β-tungsten Nb_3Si is given as 5.19 Å.

[Ref. 21457]

NIOBIUM-SILICON

SEMICONDUCTING PROPERTIES

Semiconducting Properties

Electrical Resistivity ρ ($\mu\Omega$-cm)	Thermoelectric EMF μV/°C	Hall coefficient $R \times 10^{-4}$ (cm^3/coul)	Notes	Ref.
6.3	--	--	$NbSi_2$	18173
24.5	--	--	"	13723
50.4	(α) + 14.4	-.77*	"	16993
--	(S) 13.6	--	$NbSi_2$ arc-melted	14991
--	13.7	--	$NbSi_2$ annealed	
--	8.74	--	$NbSi_{1.95}$ arc-melted	
--	10.35	--	$NbSi_{1.95}$ annealed	
--	12.4	--	$NbSi_{2.05}$ arc-melted	
--	11.57	--	$NbSi_{2.05}$ annealed	

* Hall mobility : μ_H = 1.5(cm^2/V sec)

NIOBIUM-PHOSPHOROUS

ELECTRICAL RESISTIVITY

Ripley [Ref. 11072] reports the formation of β-NbP with the following percentages: Nb-74.4% and P-24.9%. The electrical resistivity is reported in the table below.

ρ (Ω-cm)	
20°C	-197°C
1.7×10^{-3}	0.4×10^{-3}

NIOBIUM ALLOYS AND COMPOUNDS

NIOBIUM-SILICON

PHOTON EMISSION

Integral intensity of L_{β_2} bands for niobium-silicon compounds, taking L_{β_2} line for Nb as unity.

Compound	Intensity
Nb_5Si_3	0.60
$NbSi_2$ (w/impurities)	0.99

[Ref. 16347]

SECTION 4
NIOBIUM-SCANDIUM, NIOBIUM-TITANIUM & NIOBIUM-VANADIUM SYSTEMS

NIOBIUM ALLOYS AND COMPOUNDS

NIOBIUM-SCANDIUM, NIOBIUM-TITANIUM AND NIOBIUM-VANADIUM SYSTEMS

GENERAL

Nb-Sc The transition temperature given by Hake, et al [Ref. 10713] for Nb-15Sc is greater than 4.2°K. This alloy was formed by melting the components in an arc-furnace on a water cooled copper hearth, inverted and melted at least six times. Rapid quenching resulted after the arc was broken.

The critical current density measurements were taken on a cold rolled alloy reduced 85%. J_c is determined by increasing I until a slight voltage is noticed, ~0.25 μV.

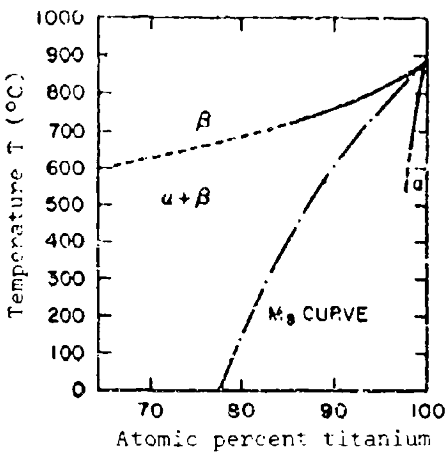
Nb-Ti The niobium-titanium system assumes a cubic structure except in the titanium rich region, 75-80 at.% titanium. The transition temperature shows the change of phase near 89% titanium and extrapolates to T_c = 0.5°K for non-alloyed titanium.

The difference between H_{c2}, the measured upper critical field, and H_{c2}*, the upper critical field from the GLAG theory, is discussed by Shapira and Neuringer [Ref. 21646].

Nb-V The niobium-vanadium system assumes an alpha phase solid solution throughout the entire range of vanadium compositions, and the lattice constants for this system decrease linearly from $a_o \simeq 3.32$ for niobium to $a_o \simeq 3.03$ for vanadium. The transition temperatures have a value of $T_c \simeq 9$°K for niobium, reach a minimum of $T_c \simeq 4$°K and then rise to $T_c \simeq 5$° for vanadium.

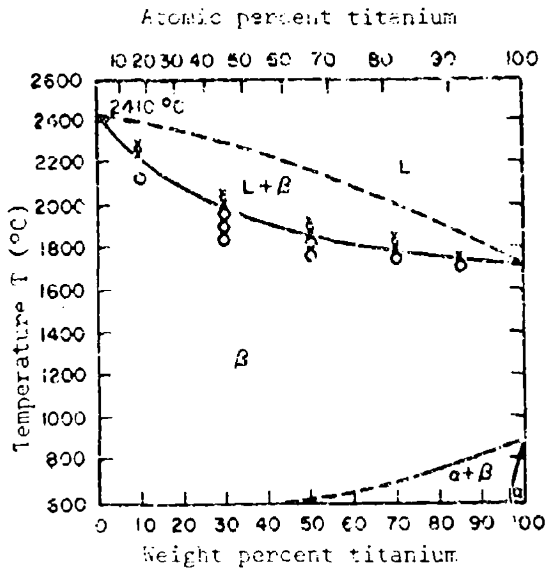
NIOBIUM-TITANIUM

GENERAL



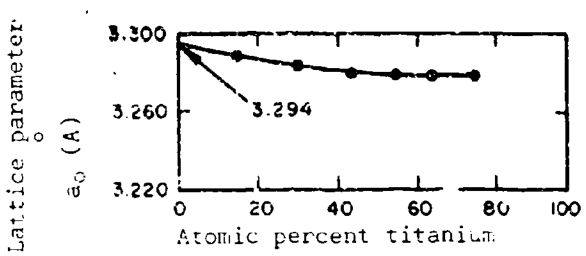
The high titanium region of the niobium-titanium phasediagram, showing the martensite curve.

[Ref. 12583]



Phase diagram for the niobium-titanium system. The phase changes from β (cubic) to mixed α (hcp) and β phases in the titanium-rich region.

[Ref. 21471]



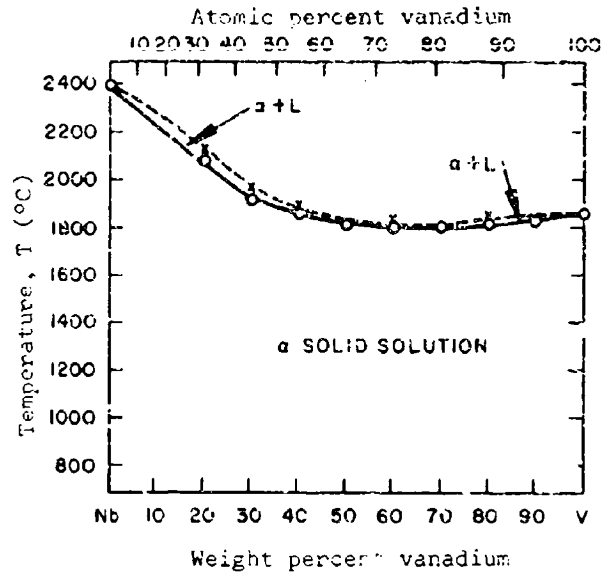
[Ref. 21471]

Lattice parameter of the niobium-titanium system as a function of titanium content.

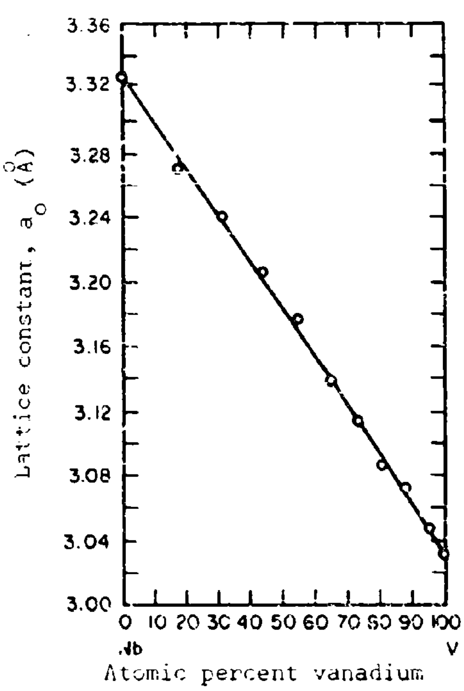
NIOBIUM-VANADIUM

GENERAL

Phase diagram for niobium-vanadium system.



[Ref. 21466]



Lattice constants for the niobium-vanadium system. Niobium in sheet or pellet form powder, was melted with sheet vanadium in an arc furnace. The alloys were remelted three or four times to increase homogeneity. Data taken above 550°C.

[Ref. 21466]

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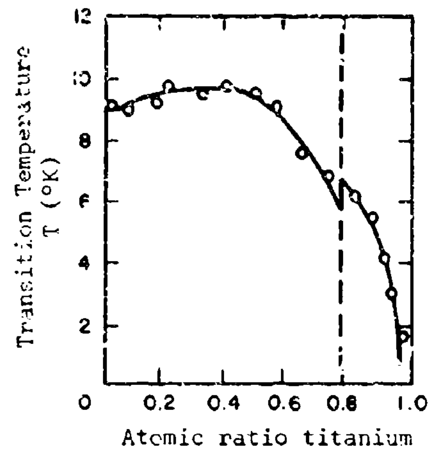
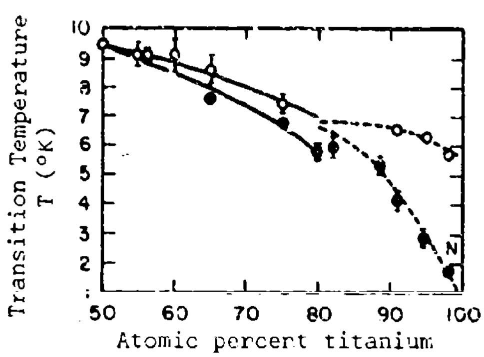
NIOBIUM-TITANIUM

TRANSITION TEMPERATURE



Transition temperatures for the niobium-titanium system, showing the phase change.

[Ref. 12583]



Transition temperatures for the niobium-titanium system in the titanium-rich zone. On extrapolation, T_c = 0.5°K for titanium.

o slow cooled

• water quenched

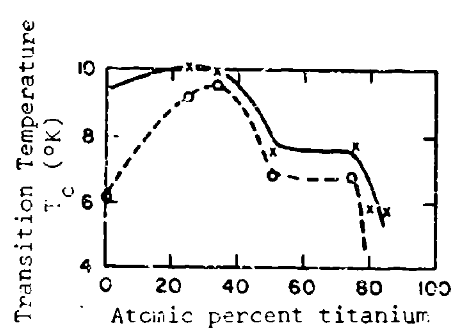
[Ref. 12583]

Transition temperature for the niobium-titanium system.

o H = 5 (KOe)

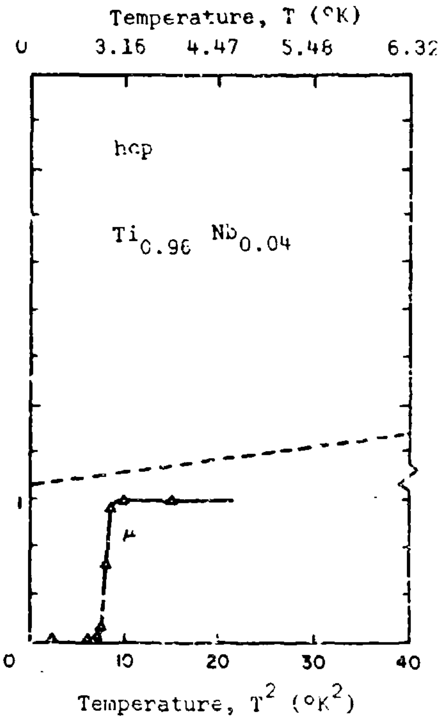
x H = 0

[Ref. 21849]



NIOBIUM-TITANIUM

TRANSITION TEMPERATURE



Transition curve for single phase hcp $Ti_{0.96}Nb_{0.04}$ from permeability measurements

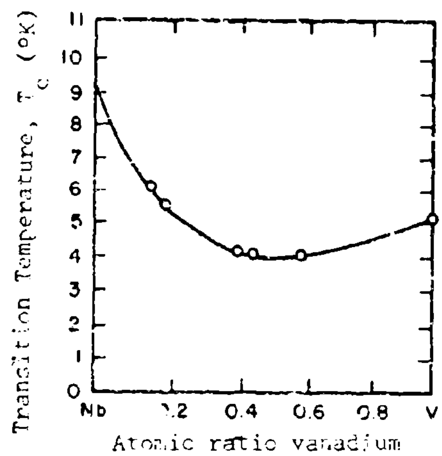
[Ref. 15532]

Lattice Constant and Transition Temperature

At.% Ti	Symmetry	Lattice Constant (Å) a_o	c_o	Transition Temperature T_c (°K)	Notes	Ref.
~80	hex	2.93	4.57	7.9	at the β-(α+β) boundary	11542
97.5	hcp	--	--	1.5	arc-melted, cold rolled, annealed 650°C, 2 hours	17310

NIOBIUM-VANADIUM

TRANSITION TEMPERATURE

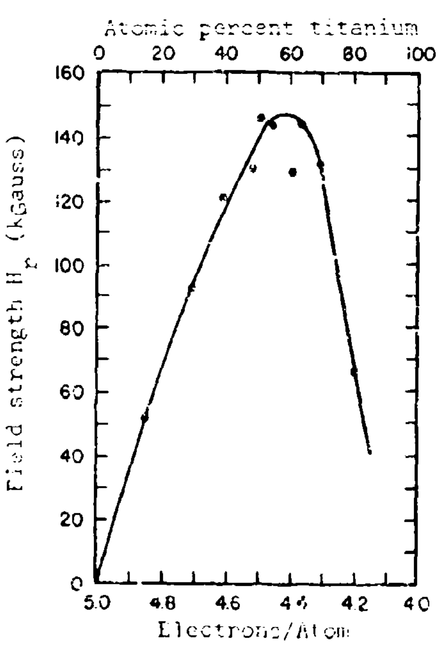


Transition temperature for niobium-vanadium system.

[Ref. 12583]

NIOBIUM-TITANIUM

CRITICAL FIELD



Field strength necessary to restore resistivity to titanium-niobium samples. The data are taken at J = 10 amp/cm^2 and T = 1.2°K.

[Ref. 15320]

NIOBIUM-TITANIUM

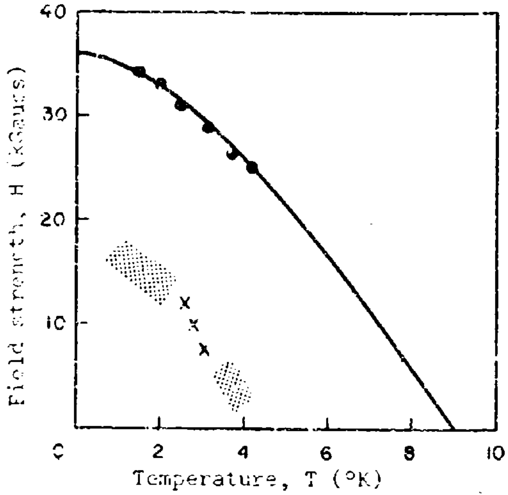
CRITICAL FIELD

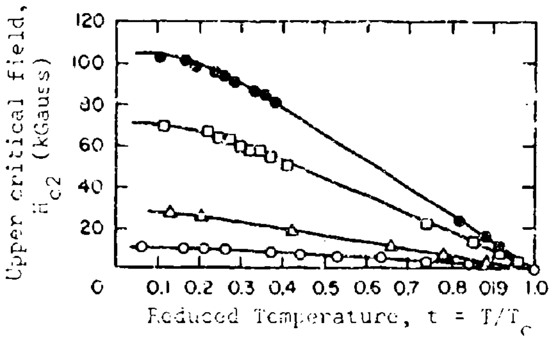
Upper critical field and resistance minima for $Nb_{.9}Ti_{.1}$, highly annealed with a small amount of defects.

X - resistance minima (these will probably extend into the shaded area)

● - $H_{c2}(T)$

[Ref. 21841]



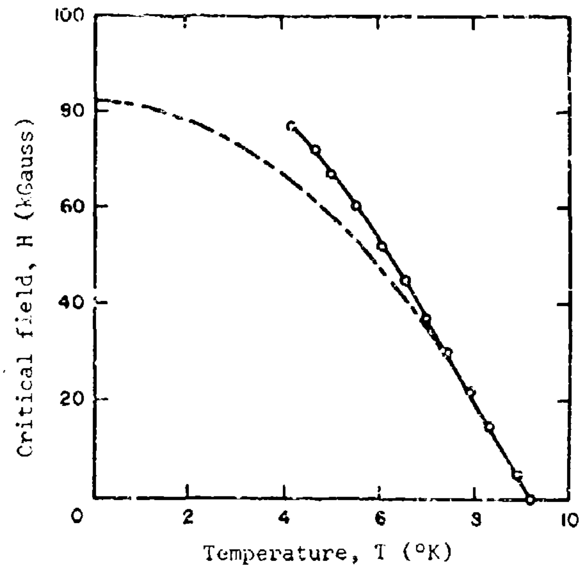


The upper critical field for niobium and three niobium-titanium alloys.

[Ref. 15470]

NIOBIUM-TITANIUM

CRITICAL FIELD

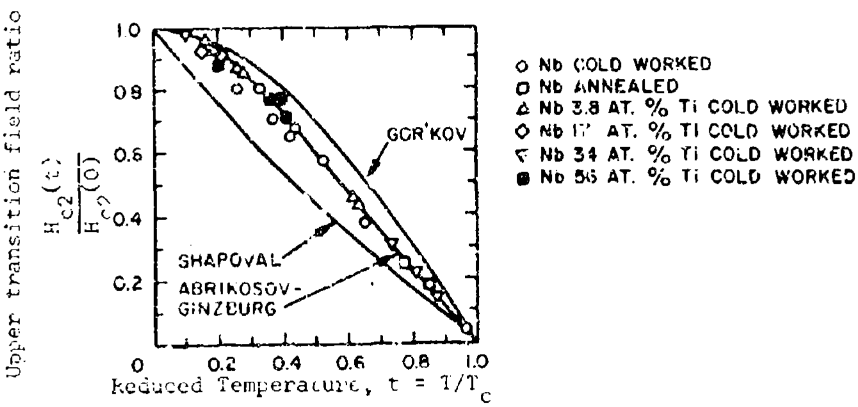


Critical field for 2Nb-Ti. Data taken at $J = 1$ to $10\ Amp/cm^2$.

$H_c = 82$ kGauss

--- $H = H_c \left[1-\left(\frac{T}{T_c}\right)^2\right]$

[Ref. 11689]

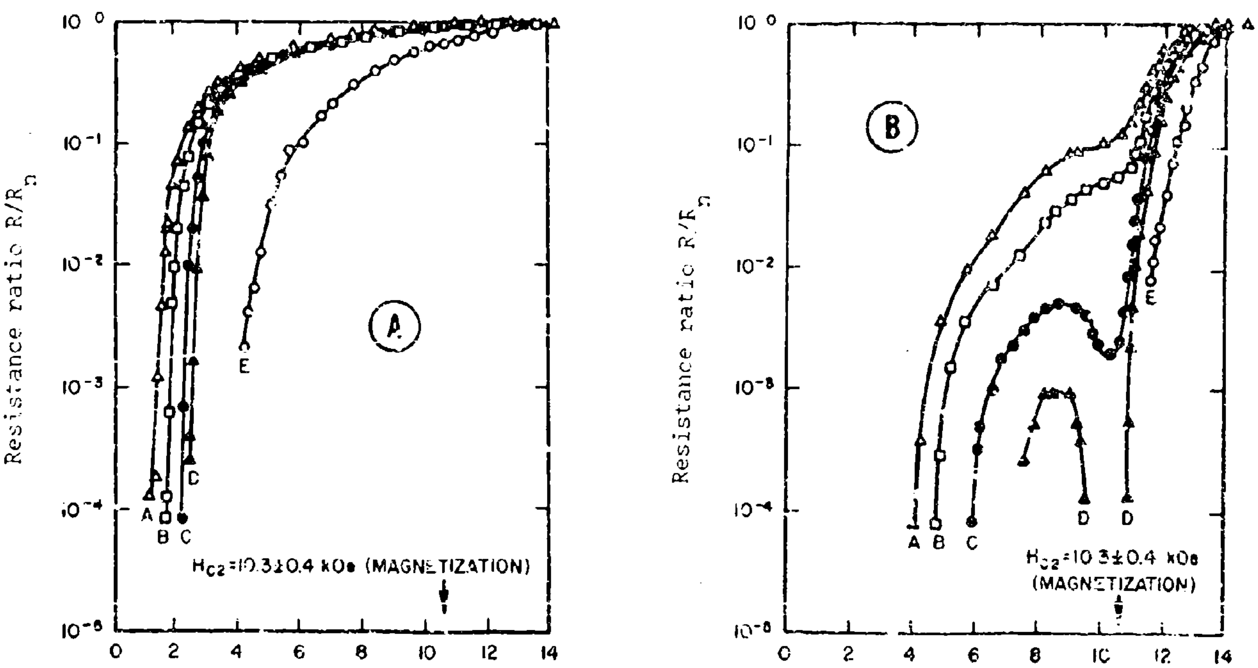


The upper critical field ratio for niobium-titanium.

[Ref. 15470]

NIOBIUM-TITANIUM

CRITICAL FIELD



Transition curves for niobium + 3.0 at.% titanium, ribbon samples.

	Ⓐ annealed		Ⓑ cold worked	
	I (A)	J (A/cm^2)	I (A)	J (A/cm^2)
A	1.62	797	1.06	797
B	0.975	480	1.00	480
C	0.43[illegible]	240	0.50	240
D	0.321	158	0.33	158
E	0.0195	9.6	0.020	9.6

[Ref. 15459]

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NIOBIUM-TITANIUM

CRITICAL FIELD

Electrical Resistivity and Critical Field

Rolled Sample

At.% Ti	ρ_n ($\mu\Omega$-cm)	Hr* (kGauss)	
5	6.8	33.2	39.9
10+	12.0	51.3	58.7
15	19.0	58.0	64.0
30	30.6	104.4	112.0
40	42.2	123.0	129.0
59.5	58.7	144.0	146.0
70.0	79.4	137.0	140.0
75.0	98.5	112.5	116.3
80.0	97.2	98.0	108.0
90.0	63.8	38.0	44.8

Wire Sample

At.% Ti	ρ_n ($\mu\Omega$-cm)	Hr* (kGauss)	
48	49.3	125.0	--
57.3	55.8	137.5	--
62.3	63.0	145.0	--
66.9	78.3	"	--
70.0	95.7	136.2	--

[Ref. 11924]

* Hr data taken at J = 10 Amp/cm^2, T = 1.2°K

+ 10 at.% titanium alloy: ρ = 13.6 $\mu\Omega$-cm, Hr = 28.1 kGauss [Ref. 16589]

NIOBIUM-SCANDIUM

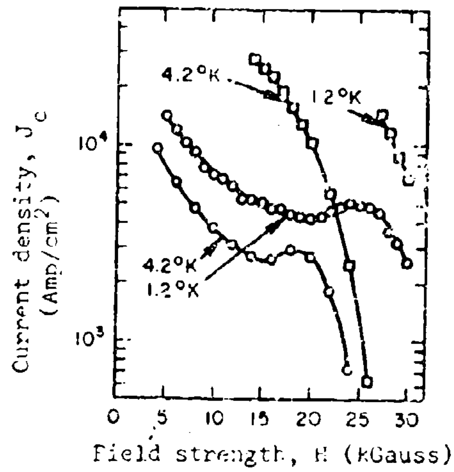
CURRENT DENSITY

Critical current density for a niobium-scandium alloy (15 at.% Sc).

O H ⊥ rolling plane

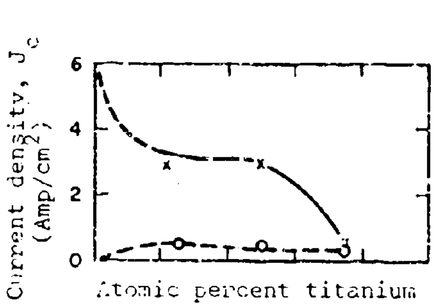
□ H ∥ rolling plane

[Ref. 10713]



NIOBIUM-TITANIUM

CURRENT DENSITY



x H = 0

o H = 5 (KOe)

Critical current density for the niobium-titanium system. Data taken at 5°K.

[Ref. 21849]

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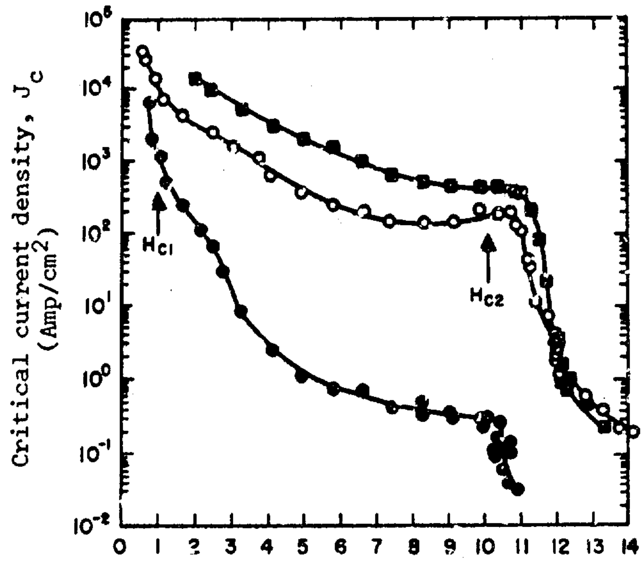
NIOBIUM-TITANIUM

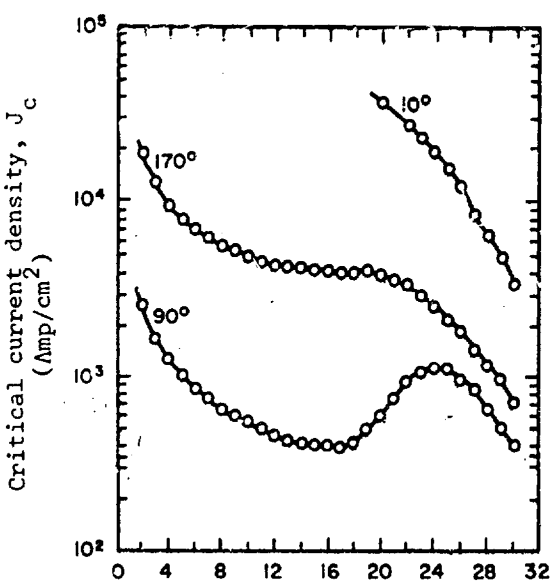
CURRENT DENSITY

Critical current density for niobium + 3.0 at.% titanium for different field orientations. The field, H is perpendicular to the current.

○ cold worked ribbon H ⊥ wide side
■ cold worked ribbon H ∥ wide side
● annealed wire

[Ref. 15459]



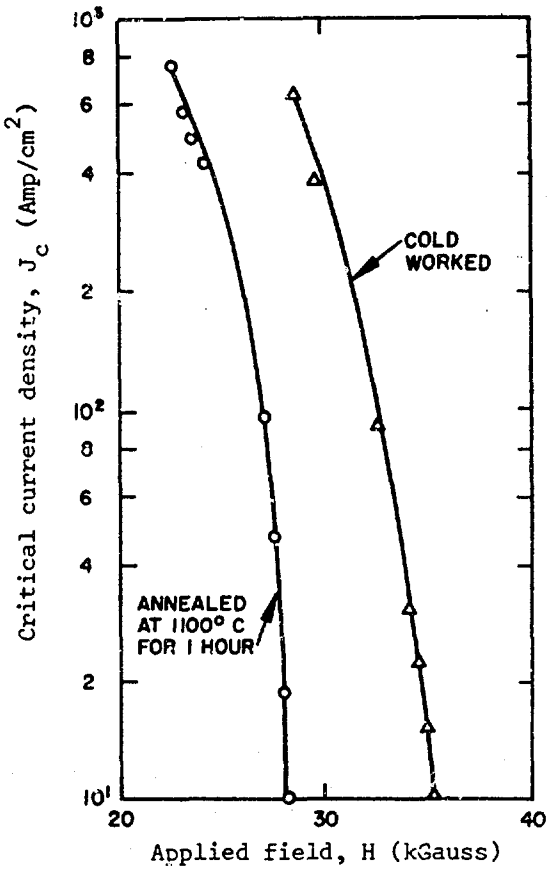


Critical current density as a function of field strength for a Nb-10 at.% Ti alloy reduced 62:1. The data were taken at 4.2°K (θ is the angle between the field and the rolling plane).

[Ref. 15344]

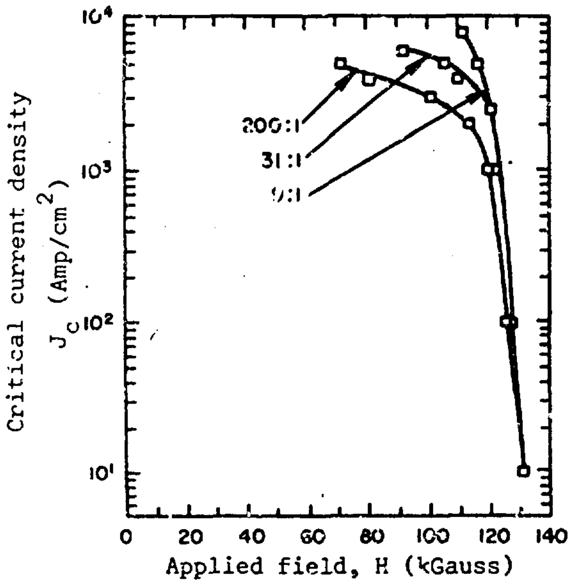
NIOBIUM-TITANIUM

CURRENT DENSITY



Critical current density as a function of transverse applied field for Nb 10 at.% Ti. Data were taken at 4.2°K.

[Ref. 16589]

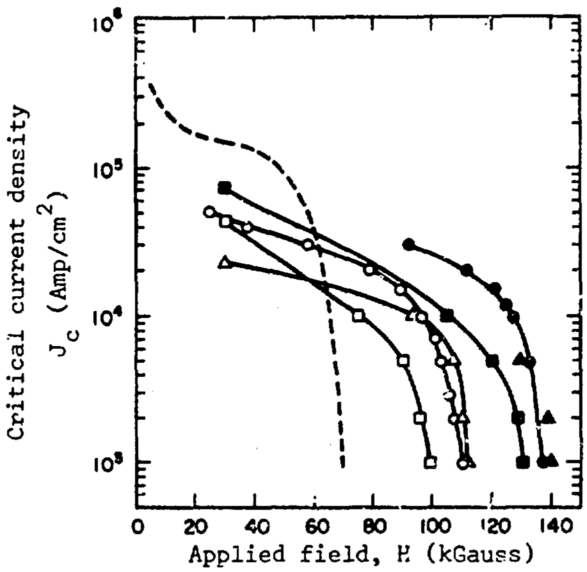


Critical current density for 35 Nb-65 Ti alloy. The data were taken at 1.2°K with H parallel to the rolling plane and perpendicular to J. The samples were cold rolled; the thickness reduction ratios are indicated on the curves.

[Ref. 15320]

NIOBIUM-TITANIUM

CURRENT DENSITY



Critical current density as a function of transverse applied field.

1.2°K	4.2°K	
■	□	$Nb_{.30}Ti_{.70}$ 0.010 in. diam. wire
▲	△	$Nb_{.39}Ti_{.61}$ 0.0051 in. diam. wire
●	○	$Nb_{.50}Ti_{.50}$ 0.0016 thick strip reduced 275:1 by cold rolling, H‖ rolling plane
- - - - - - - - - - - -		$Nb_{.75}Zr_{.25}$ for comparison

[Ref. 15320]

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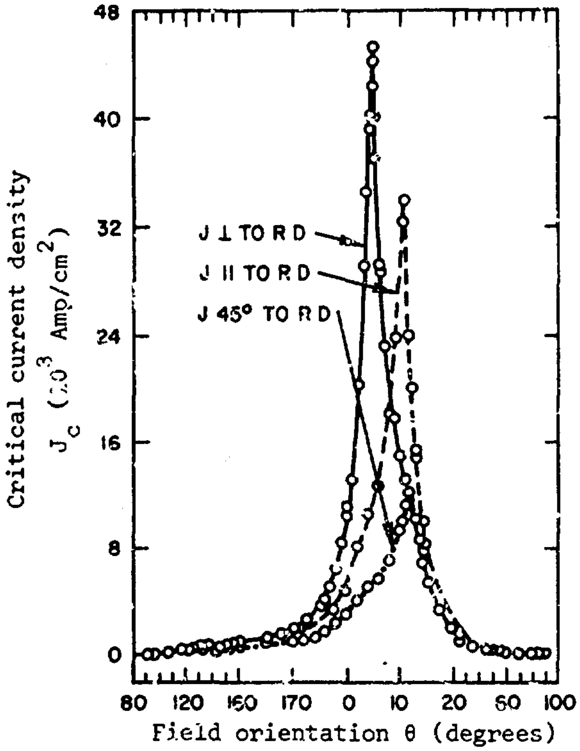
NIOBIUM-TITANIUM

CURRENT DENSITY



Critical current density for three Nb-40 at.% Ti alloys as a function of the angle between applied field and rolling plane.

H = 30 kGauss

T = 4.2°K

J ∥ R.P.

H ⊥ J

240 : 1 reduction

[Ref. 15344]

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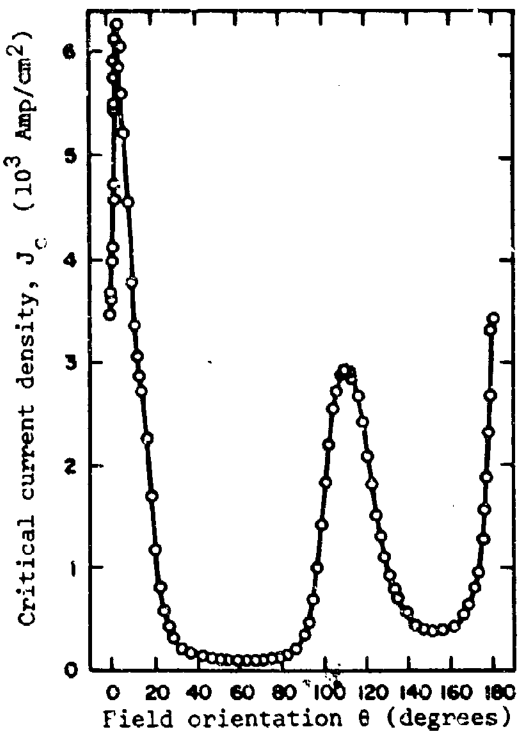
NIOBIUM-TITANIUM

CURRENT DENSITY

Critical current density for a Nb-40 at.% Ti alloy as a function of the orientation of H with the rolling plane of the sample.

H ⊥ rolling direction
J || rolling direction
H = 30 kGauss
T = 4.2°K
24 : 1 reduction

[Ref. 15344]



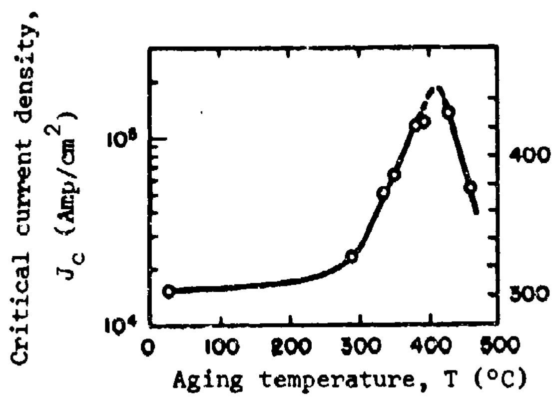
Critical Current Density
J_c (10^3 Amp/cm^2)

Ti	Rolling Plane H∥	H⊥	Unrolled	Reduction	T°K	Notes
80%	4.8	4.4	--	89%	1.2	30 kGauss standard sample preparation
65	4.6	0.38	0.10	90	4.2	
50	1.4	0.12	0.16	92	"	
28	3.5	0.10	0.12	90	"	

[Ref. 10713]

NIOBIUM-TITANIUM

CURRENT DENSITY



A niobium-titanium alloy (79.3 at.% Ti) was machined, slightly rolled and recrystallized at 800°C. Further rolling (80%) and aging at temperatures, shown on the above graph, markedly affect the critical current density and upper critical field.

H_{c2} before annealing 110kG (1.2°K)

H_{c2} after annealing 128kG (1.2°K)

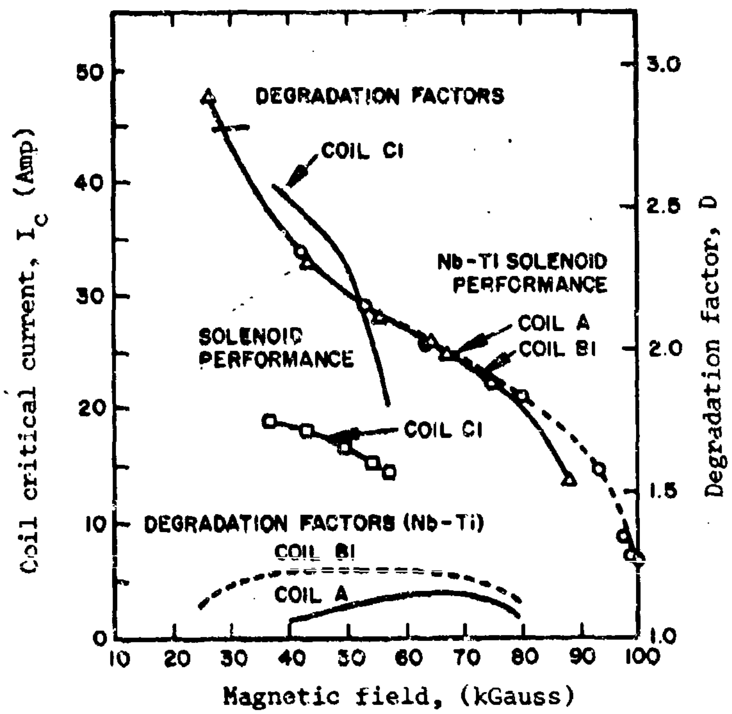
Data Taken

H = 30 kGauss
T = 4.2 °K

[Ref. 19868]

NIOBIUM-TITANIUM

CURRENT DENSITY



Characteristics of niobium-titanium wires wound into solenoids 4.250 in long.

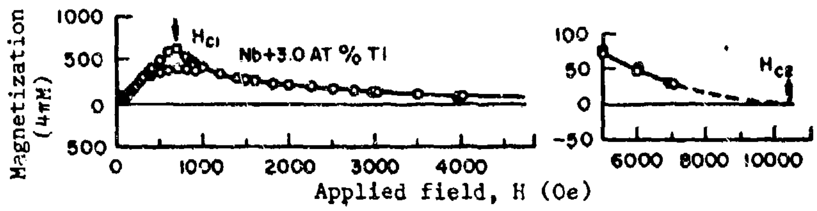
Coil	o.d.	i.d.	Turns	Wire
A	0.986 in.	0.194 in.	10878	Nb-56% Ti
B1	2.637	1.105	17768	Nb-61% Ti
C1	5.261	3.729	21076	Nb-25% Zr (for comparison)

$$D = \frac{I_c \text{ (short wire)}}{I_c \text{ (coil)}}$$

[Ref. 19479]

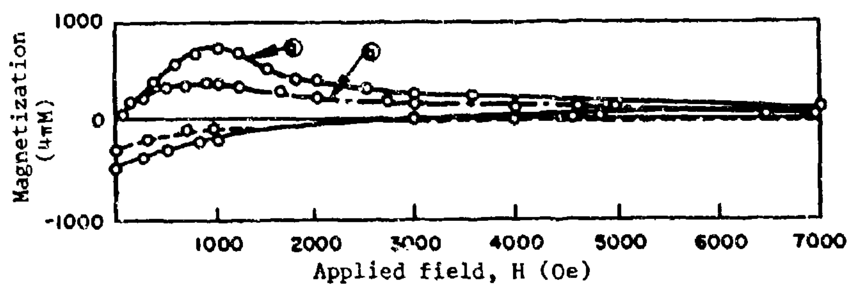
NIOBIUM-TITANIUM

MAGNETIC HYSTERESIS



Magnetization for niobium + 3.0 at.% titanium wires. Homogenized by passing large currents through the samples at $<10^{-6}$ mm Hg vacuum for 4 hours at 1700°C.

[Ref. 15459]



Magnetization as a function of applied field for a niobium-10 at.% titanium alloy. Data taken at 3.56°K.

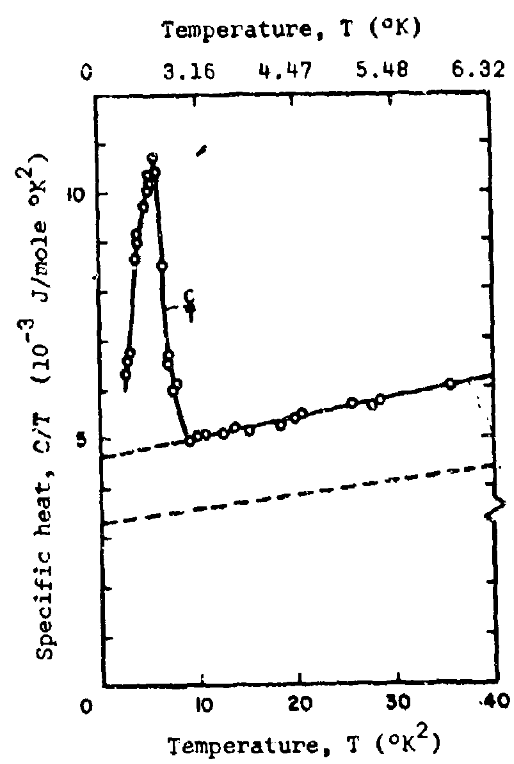
a) Rods, 1.2 cm long, 0.6 cm diameter

b) Powder, 45-60 μ particle size

[Ref. 10778]

NIOBIUM-TITANIUM

SPECIFIC HEAT



Specific heat for single phase, hcp, $Ti_{0.96}Nb_{0.04}$ as a function of temperature.

[Ref. 15532]

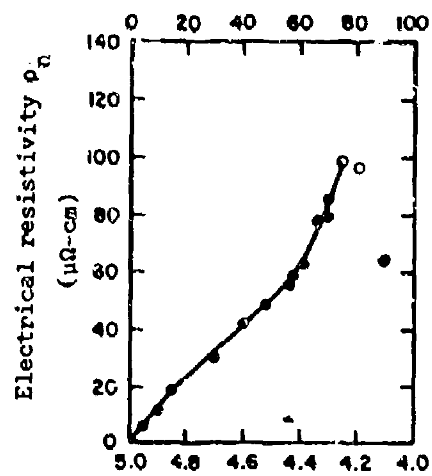
Magnetic and Thermal Data

At.% Ti	Coefficient of electronic specific heat, γ (J mole^{-1} °K^{-2})	Debye Temperature θ (°K)	Atomic susceptibility χ (Nb-Ti) / χ (Ti)	Atomic susceptibility χ (Nb-Ti, 10°K) / χ (Nb-Ti, 300°K)
96	4.3	340	1.05	0.92

[Ref. 15532]

NIOBIUM-TITANIUM

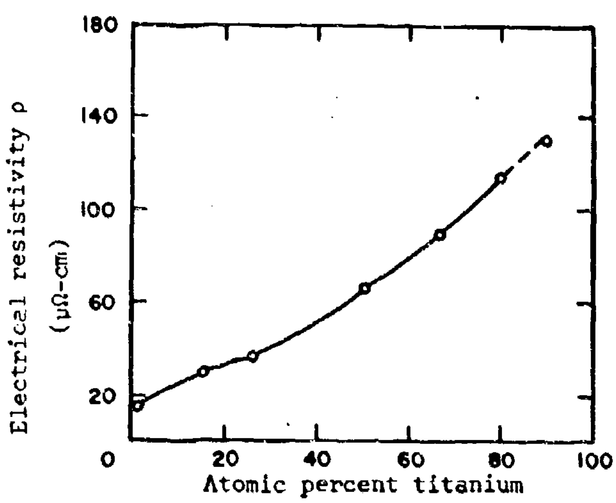
ELECTRICAL RESISTIVITY



Electrical resistivity for the niobium-titanium
Data taken at 1.2°K.
Standard sample preparation.

o two phase
• single phase

[Ref. 11924]

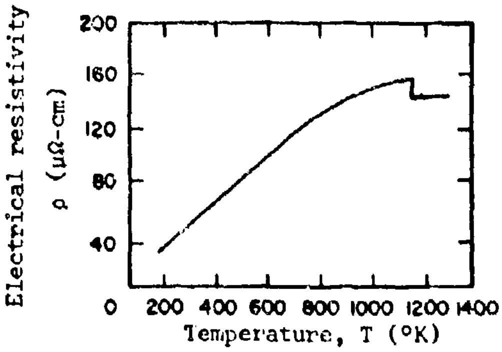


Electrical resistivity for the niobium-titanium system as a function of titanium content.

[Ref. 21728]

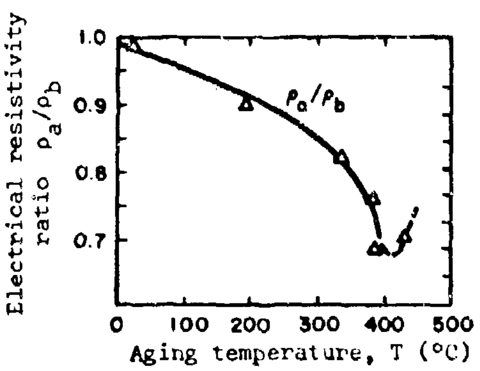
NIOBIUM-TITANIUM

ELECTRICAL RESISTIVITY



Electrical resistivity for a niobium-titanium alloy with less than ∿35% niobium. The samples were arc-melted, worked, annealed for 20 hours at 100°C, then quenched.

[Ref. 21728]

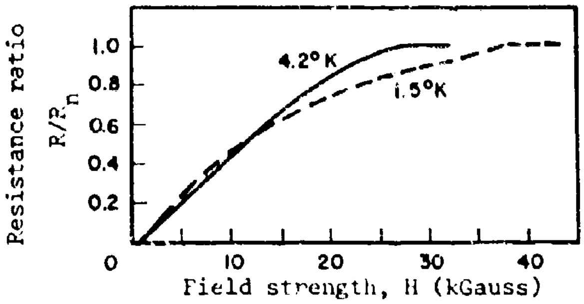


A niobium-titanium alloy (79.3 at.% Ti) is prepared as follows: The components are arc-melted together, machined, slightly rolled and recrystallized at 800°C. The sample then undergoes further rolling (80%) and aging at the temperature shown on the graph. ρ_a is the resistivity prior to aging and ρ_b after aging.

[Ref. 19868]

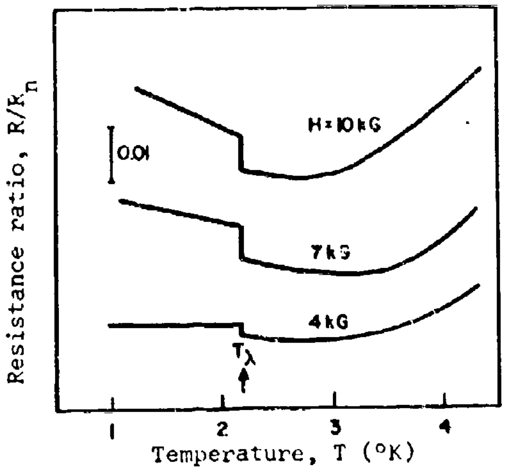
NIOBIUM-TITANIUM

ELECTRICAL RESISTIVITY



Resistance ratio as a function of field strength for highly annealed $Nb_{.9}Ti_{.1}$ with small amount of defects.

[Ref. 21841]



Resistance minir a for $Nb_{.9}Ti_{.1}$, highly annealed with small amount of defects. R/R_n is relative, with the vertical scale corresponding to R/R_n = 0.01. The discontinuity in the constant field curves corresponds to the λ point of liquid helium, T_λ = 2.19°K.

[Ref. 21841]

SECTION 9

NIOBIUM-GALLIUM &

NIOBIUM GERMANIUM SYSTEMS

NIOBIUM ALLOYS AND COMPOUNDS

NIOBIUM-GALLIUM AND NIOBIUM-GERMANIUM SYSTEMS

GENERAL

Nb-Ga Niobium-gallium in the β-tungsten structure shows a transition temperature near 14°K. None of the other Nb-Ga compositions give any indication of being superconductive. The data given in this section also show the effect of alloying Nb_3Ga with germanium and tin.

Nb-Ge Three compounds are formed in the niobium-germanium systems, Nb_3Ge with a β-tungsten phase, tetragonal Nb_5Ge_3 and hexagonal $NbGe_2$. The exact nature of the eutectic points and decomposition temperature of these niobium compounds has not been determined. Much of the work by Carpenter [Ref. 20020 and 20022] has helped, but explicit phase diagram data is still lacking.

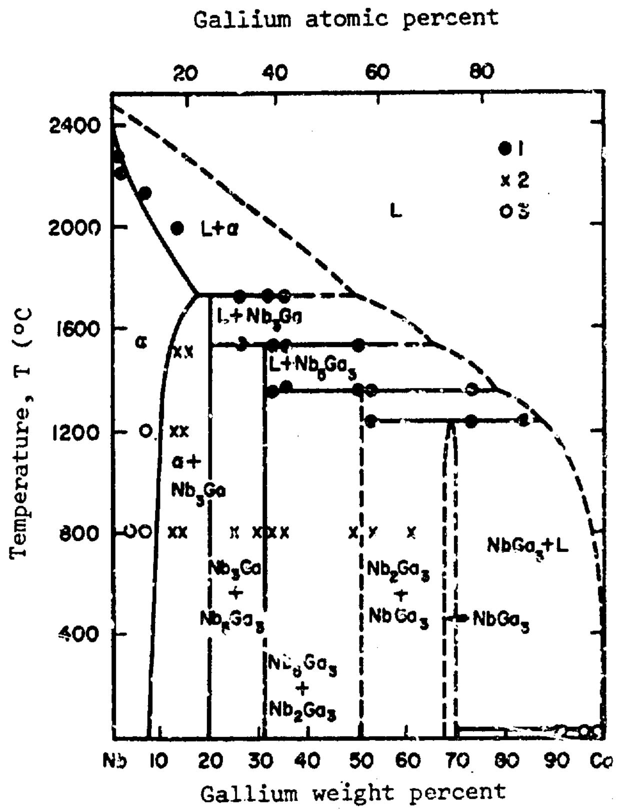
Carpenter [Ref. 20022] claims that the solid solution range of Nb_3Ge extends from $NbGe_{0.15 \pm 0.01}$ to $NbGe_{0.22 \pm 0.02}$ i.e., from 13 to 18 atomic percent germanium. The lattice constants in this range are given.

Of the three structures, the β-tungsten (Nb_3Ge) shows the highest transition temperature in the 5-7°K range. This temperature is raised markedly by the addition of other elements, such as tin and aluminum. The tetragonal Nb_5Ge_3 compound shows no transition temperature above 1°K even with the addition of carbon or zirconium.

[Ref. 12216]

NIOBIUM-GALLIUM

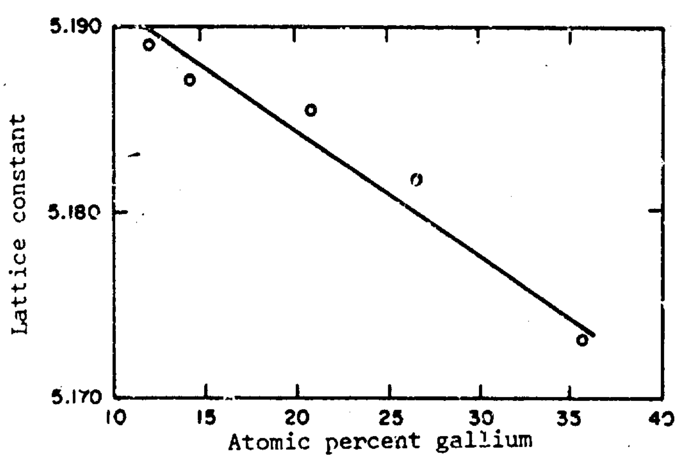
GENERAL



Phase diagram for the niobium-gallium system.

1 thermal analysis results
2 two phase alloys
3 single phase alloys

[Ref. 21729]

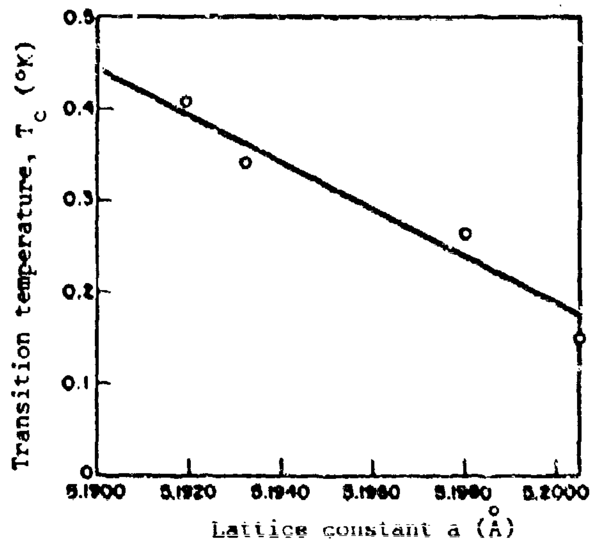


Lattice constant of Nb_3Ga as a function of niobium content. The sample was prepared by chemical vapor deposition method.

[Ref. 21843]

NIOBIUM-GALLIUM

TRANSITION TEMPERATURE



Transition temperature as a function of lattice constant for chemical vapor-deposited Nb_3Ga.

[Ref. 21843

NIOBIUM-GALLIUM-M

LATTICE CONSTANT AND TRANSITION TEMPERATURE

Lattice Constant and Transition Temperature

Formula	Symmetry	Lattice Constant a_o	Transition Temperature T_c	width	Notes	Ref.
Nb_3Ga	β-tungsten	5.171 ± .002	14.5	-	Nb powder melted w/Ga at 1200°C, fused in He atm. arc furnace.	14387
Nb_3Ga	"	..	13.2	4.6	3 hours at 1800°C	13155
$Nb_3Ga_{.5}Ge_{.5}$	"	5.175	7.3	-	Formed at 1800°C	13155
Nb_6GaSb	-	-	9.2 - 10.6		Prepared by HCl transparent	21843
Nb_6GaP	-	-	9.3 - 11.2		Prepared by HCl transparent	21843

$Nb_3Ga_xSn_{1-x}$ - - - - 13155

Gallium component x	16 hours, 1200°C a_o	T_c	*ΔT_c	3 hours, 1500°C a_0	T_c	ΔT_c
1.00					†12.5[a]	1.6
.8					†13.1	2.6
.6		†14.0	4.7	5.230	14.6	0.6
.4	5.287	13.5	3.3	5.262	16.0	0.7
.3	**5.272					
.2	5.282	17.8	0.9	5.282[a]	17.4	0.7
.1	**5.274	18.1	0.9		15.3[b]	1.0

* ΔT_c width of the transition region

† not single phase

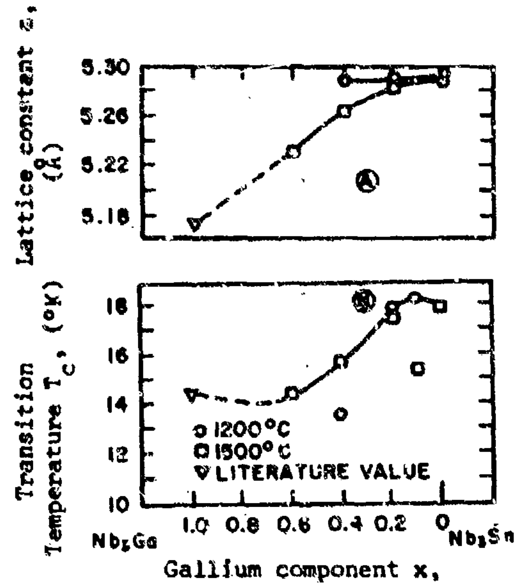
** [Ref. 7888]

a after 1200°C firing the sample was refired for 7 hours at 1500°C

b after 1200°C firing the sample was refired for 3 hours at 1500°C

NIOBIUM-GALLIUM-M

LATTICE CONSTANT AND TRANSITION TEMPERATURE



Lattice constant and transition temperature as a function of x, $Nb_3Ga_xSn_{1-x}$. Samples sintered.

[Ref. 13155]

NIOBIUM-GERMANIUM-M

LATTICE CONSTANT AND TRANSITION TEMPERATURE

Formula	At.% Ge	Crystal-lography	Lattice constant (Å) a_o	c_o	Transition Temperature T_c (°K)	Notes	Ref.
Nb_5Ge_3 + C	42.5	$D8_8$	7.6	5.3	<1.1	--	17475
$Nb_{2.5}Zn_{2.5}Ge_3$	42.5	--	7.89	5.43	<1.1	--	"
$Nb_3Ge_{.5}Ga_{.5}$	12.5	β-tungsten	5.175	--	7.3	Prepared at 1800°C	13155
$Nb_3Ge_{.5}Al_{.5}$	12.5	β-tungsten	5.175	--	12.6	Pressed & sintered 3 hours, 1500°C	"
$Nb_3Ge_{.5}Sn_{.5}$	12.5	β-tungsten	5.236	--	12.6	Arc-melted	"
$Nb_3Ge_{.5}Sn_{.5}$	12.5	β-tungsten	--	--	11.3	--	10704

NIOBIUM-GERMANIUM

TRANSITION TEMPERATURE

Lattice Constant and Transition Temperature

At.% Ge	Symmetry	Lattice constant (Å) a_o	Lattice constant (Å) c_o	Transition Temperature T_c (°K)	Notes	Ref.
13.63	β-tungsten	5.1756 ± .001	-	-	Nb_3Ge w/ excess Nb $NbGe_{.159 \pm .003}$	20022
13.75		5.174	-	4.9	$Nb_3Ge_{.55}Nb_{.45}$ heated 1600°C, 6 hours	7888
18.0		5.166	-	5.4	$Nb_3Ge_{.72}Nb_{.28}$	7888
18.9		-	-	5.3	$NbGe_{.22}$	12421
25.0		5.168 ± .002	-	-	Nb_3Ge stable to 1910°C	20020
"		-	-	6.9	-	12216
"		-	-	12.6	-	7888
∿29		5.149	-	>17	Arc-cast rapidly quenched and annealed up to 1000°C	21469
37.5	tetragonal	10.148	5.152	<1.02	Nb_5Ge_3	12216
67	hexagonal	4.966 ± .003	6.781 ± .003	-	$NbGe_2$ decomposes at 1483 ± 15°C	20020

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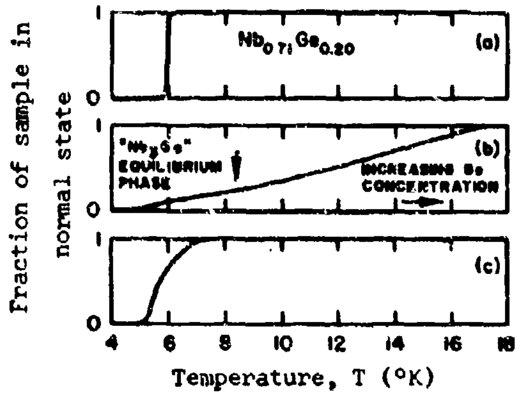
NIOBIUM-GERMANIUM

TRANSITION TEMPERATURE

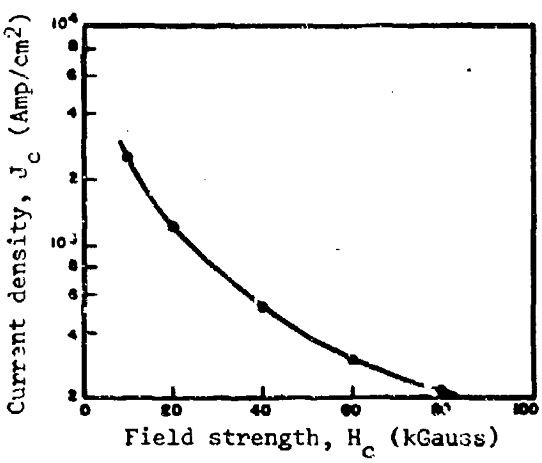
Stoichiometric niobium germanium compounds were formed with a normal composition of 25-29% Ge. (a) shows the transition when the samples were arc-cast, (b) shows the same samples rapidly quenched and variously annealed up to 1000°C, (c) show the results of annealing this same sample to 1100°C for three days.

[Ref. 21469]



NIOBIUM-GALLIUM

CURRENT DENSITY



Current density as a function of field strength for cast Nb_3Ga at 4.2°K. These J_c values are highly dependent upon sample preparation.

[Ref. 10708]

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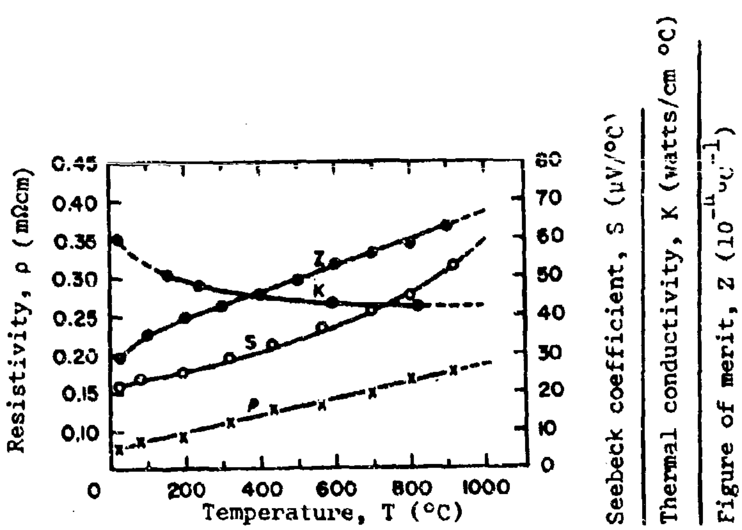
NIOBIUM-GERMANIUM-SILICON

THERMOELECTRIC PROPERTIES

Formula	Lattice constants (Å) a_o	c_o	Electrical resistivity (mΩ-cm) 25°C	196°C	Seeback coefficient (μ V/C°)	Thermal conductivity K (watts/cm °C) 25°C	Figure of merit (10^{-5} °C^{-1}) 25°C
$NbGe_2$*	4.943	6.778	0.067	0.031	+ 12	0.31	0.70
$NbGe_{1.5}Si_{0.5}$	4.910	6.730	0.077	0.063	+ 17	0.19	2.0
$NbGe_{1.0}Si_{1.0}$	4.885	6.682	0.081	0.065	+ 22	0.16	3.7
$NbGe_{0.5}Si_{1.5}$	4.834	6.635	0.060	0.047	+ 20	0.20	3.3
$NbSi_{2.0}$	4.803	6.604	0.098	0.063	+ 19	0.42	0.9

* These materials have a C 40 type structure

[Ref. 20159]



Thermoelectric properties of $NbSi_{1.0}Ge_{1.0}$ as a function of temperature. The samples were pressed and sintered.

x - Resistivity o - Seebeck coefficient ⊙ - Thermal conductivity
● - Figure of merit

[Ref. 20159]

SECTION 4
NIOBIUM-CHROMIUM & NIOBIUM-IRON SYSTEMS

NIOBIUM ALLOYS AND COMPOUNDS

NIOBIUM-CHROMIUM AND NIOBIUM-IRON SYSTEMS

GENERAL

Nb-Cr Niobium when alloyed with chromium shows little promise as superconducting material. As the chromium content increases the transition temperature drops linearly from the T_c value for niobium and appears to reach zero at 20 at.% chromium.

The niobium-chromium system shows only one compound, $NbCr_2$ with a cubic $MgCu_2$ (C 15) type structure. This compound exists beyond the alloy region of superconductivity.

Nb-Fe Lattice constants are given for only intermetallic phase in the niobium-iron system. Wallbaum* gives a_o = 4.830 (Å) and c_o = 7.882 Å for $NbFe_2$ ($MgZn_2$ type structure). These values are corroborated by Elliot†; a_o = 4.834 and c_o = 7.880.

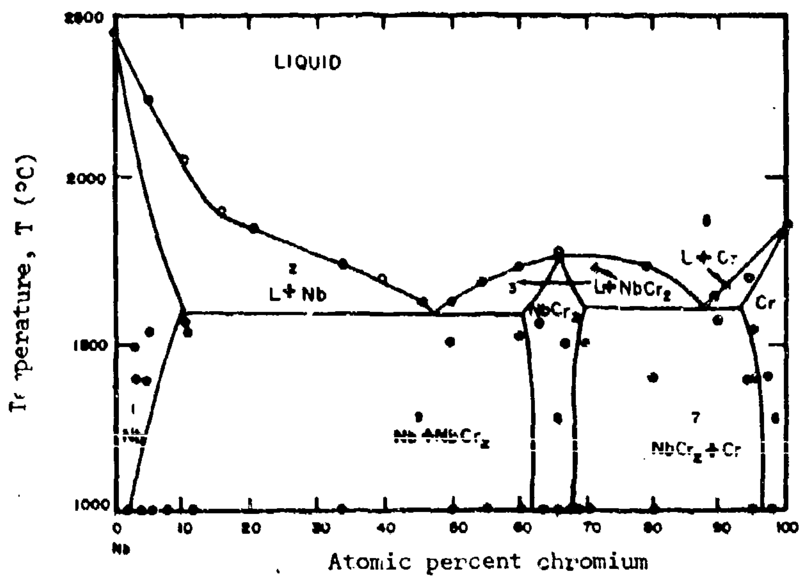
Other phases are reported to exist in this binary system but they are stable only at high temperatures and lattice constants are not available.

* Wallbaum, H.J., Z. KRIST., v. 103, 1941. p. 391-402.

† Elliot, R.P., Armour Research Foundation, Chicago. TR1 OSR Technical note OSR-TN-247, August 1964. p. 19.

NIOBIUM-CHROMIUM

GENERAL



Phase diagram for niobium-chromium system. $NbCr_2$ ranges from 64-70 at.% chromium.

o measured melting points

• identified alloys

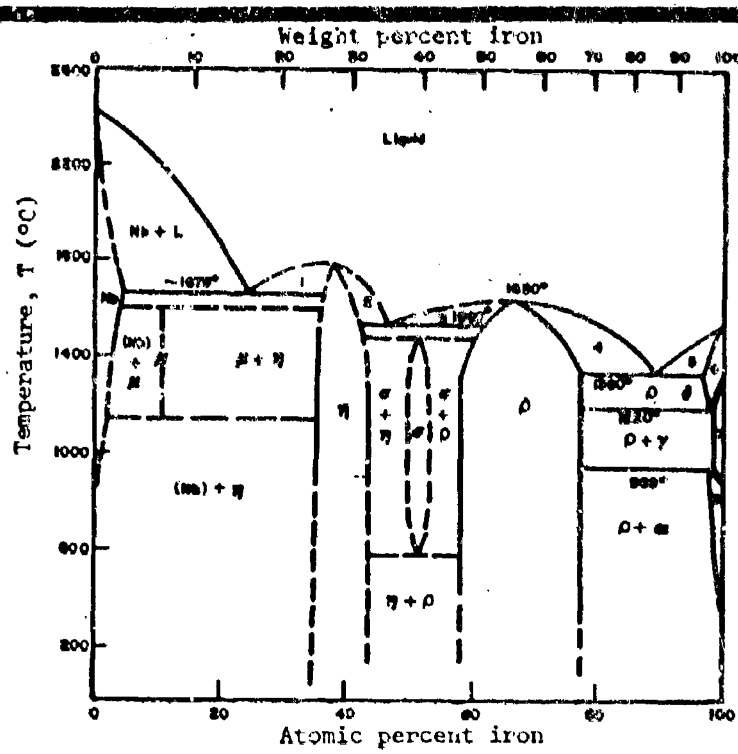
[Ref. 19469]

NIOBIUM-IRON

GENERAL

Phase diagram for the niobium-iron system

1) L + η
2) η + L
3) ρ + L
4) ρ + L
5) δ + L
6) δ
7) γ
8) α



[Ref. 19926]

NIOBIUM-CHROMIUM

GENERAL

Lattice Constants

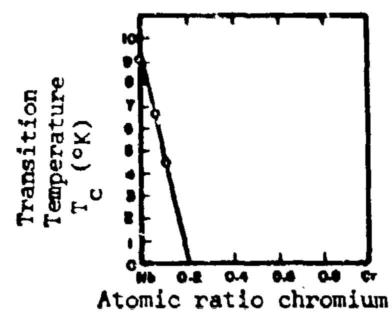
Formula	Lattice constant (Å) a_o	Ref.
Nb ⇄ $NbCr_2$	7.001	19469
$NbCr_2$	6.985	Hansen
$NbCr_2$ ⇄ Cr	6.981	19469

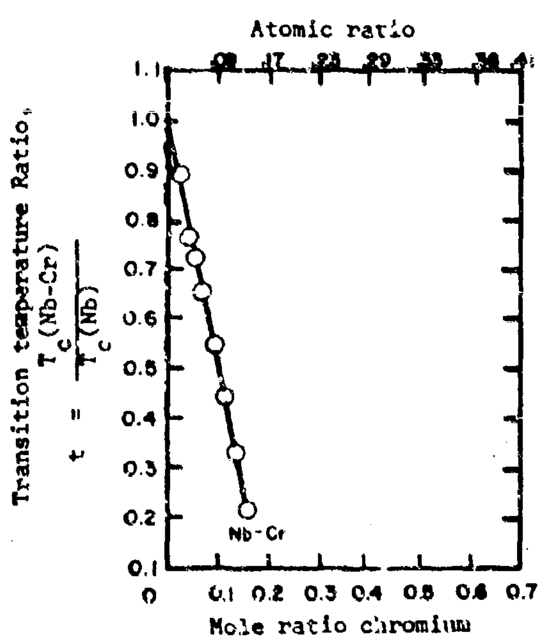
NIOBIUM-CHROMIUM

TRANSITION TEMPERATURE

Transition temperature of niobium-chromium samples, arc-melted and unannealed.

[Ref. 12583]



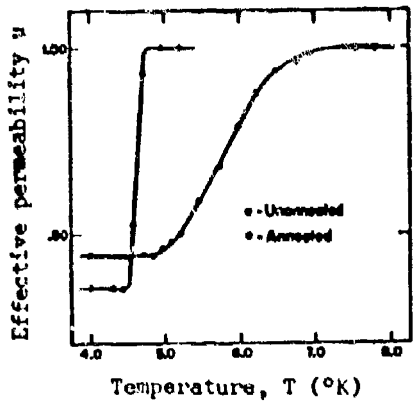


Transition temperature of niobium chromium systems, arc melted and unannealed.

[Ref. 10778]

NIOBIUM-CHROMIUM

TRANSITION TEMPERATURE

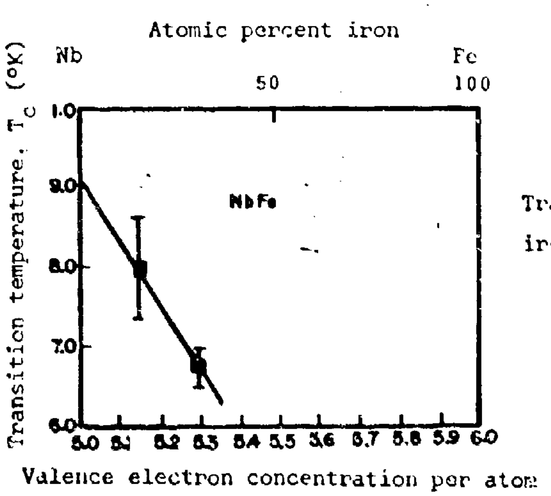


Annealing effect on the transition temperature of a 10 at.% chromium alloy.

[Ref. 12583]

NIOBIUM-IRON

TRANSITION TEMPERATURE



Transition temperature of niobium-iron samples.

[Ref. 14468]

SECTION 4
NIOBIUM ARSENIC &
NIOBIUM-SELENIUM SYSTEMS

NIOBIUM ALLOYS AND COMPOUNDS

NIOBIUM-ARSENIC AND NIOBIUM-SELENIUM SYSTEM

GENERAL

Nb-As Although niobium and arsenic form "mono" and "di" arsenides, neither shows superconductivity. The only data given here are for the lattice constants and magnetic susceptibility.

Nb-Se The niobium selenium system in the niobium rich region shows no evidence of being superconducting above 4.2°K [Ref. 13150]. In the $NbSe_{1.90}$ - $NbSe_{2.25}$ region there is an indication that a transition temperature exists near 4.2°K. Single crystals of the system in this range, prepared by a vapor transport method, show a nominal $NbSe_2$ composition and have a T_c of 4.2°K.

This system forms into layer type crystals with various polytypes. The lattice constants and transition temperature are given for some compounds.

NIOBIUM-ARSENIC

GENERAL

Compound	At.% As	Symmetry	Lattice constants (Å) a_o	b_o	c_o	β	Notes
NbAs	50	tetragonal	3.45 ± .001	--	11.65 ± 0.02	--	*
$NbAs_2$	67	monoclinic	9.365 ± 0.02	3.38 ± 0.01	7.809 ± 0.02	119°26'	--

Ref. Saint, G.S., et al. CAN. J. CHEM., v. 42, p. 630, 1964. * single crystal

NIOBIUM-SELENIUM

GENERAL

Formula	Lattice constant (Å) a_o	c_o
α-$NbSe_2$	3.449	12.998
β-$NbSe_2$	3.439	25.188

[Ref. 21796]

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NIOBIUM-SELENIUM

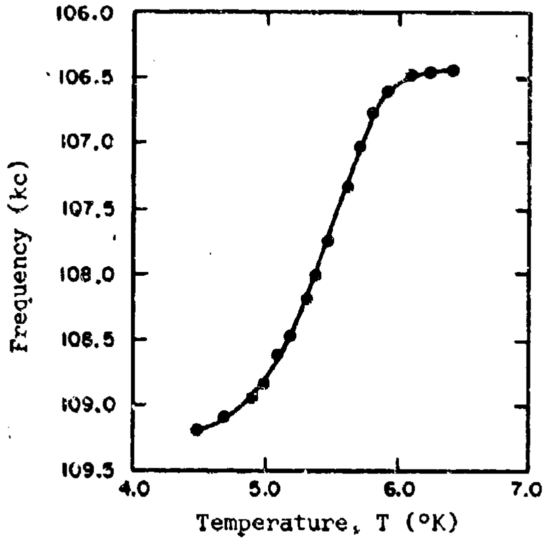
TRANSITION TEMPERATURE

Lattice Constant and Transition Temperature

Lattice constant (Å) a_o	c_o	Transition temperature T_c (°K) midpoint	onset	complete	At.% Se	Symmetry	Notes	Ref.
3.437	13.030	--	--	--	50	hex	--	21796
3.44	12.54	5.47	5.62	5.15	67	"	Powders were sealed in evacuated quartz ampules & sintered for 72 hours at 600 - 800°C.	13150
3.44 ± .01	25.24 ± .04	6.0	--	--	67		Vapor transport process.	18755

NIOBIUM-SELENIUM

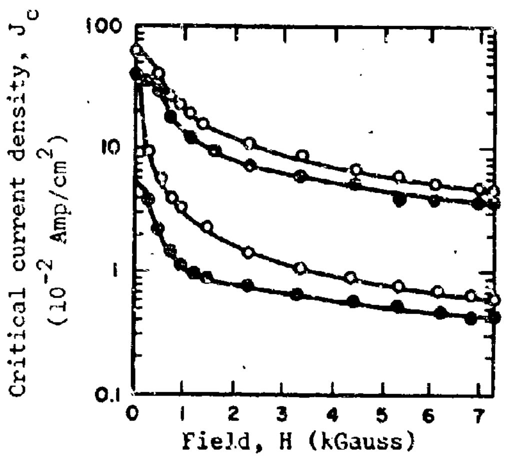
TRANSITION TEMPERATURE



Transition curve for $NbSe_2$ from resonance coil measurements. Nb and Se powders were sealed in evacuated ampules and sintered for 72 hours at 600-800°C.

[Ref. 13150]

NIOBIUM-SELENIUM
CURRENT DENSITY



Critical current density for two $NbSe_2$ crystals.

● width to thickness ratio = 9
o = w/t = 15
(a) H ⊥ c-axis
(b) H || c-axis
T = 4.2°K
J || a-axis

[Ref. 18755]

NIOBIUM-SELENIUM

CURRENT DENSITY

Critical current density for a $NbSe_2$ crystal with different leads.

Δ Cu leads; indium soldered

o Ni leads; spot welded

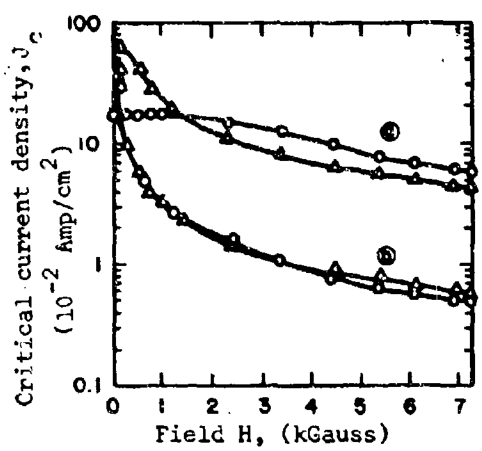
(a) H ⊥ c-axis

(b) H ∥ c-axis

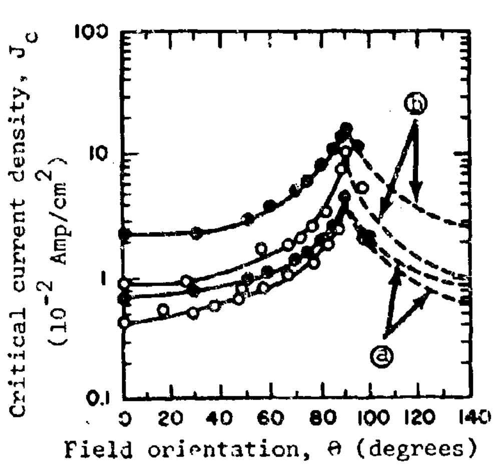
T = 4.2°K

w/t = 9

J ∥ a-axis



[Ref. 18755]



Critical current density for two $NbSe_2$ Crystals.

• = w/t = 9

o = w/t = 15

T = 4.2°K

J ∥ a-axis

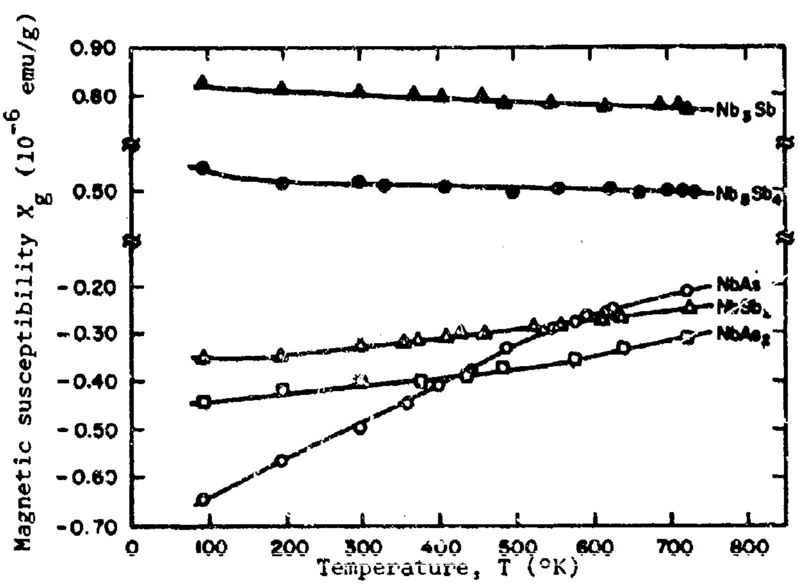
a) H = 1.4 kGauss

b) H = 7.25 kGauss

[Ref. 18755]

NIOBIUM-ARSENIC

MAGNETIC SUSCEPTIBILITY

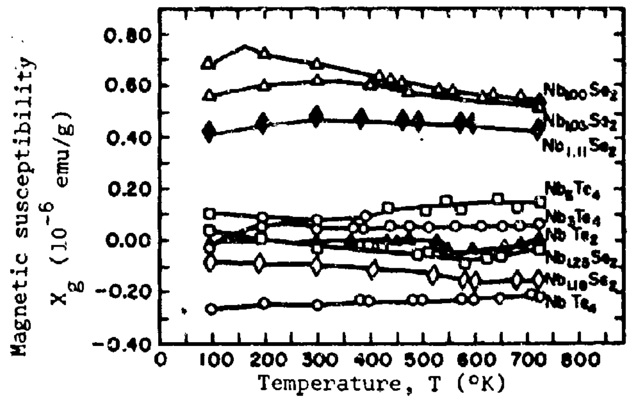


Magnetic susceptibility for niobium antimonides and arsenides as a function of temperature. The antimonides were prepared by heating niobium and antimony at 1000°C for 2 days, 800°C for 14 days and quenching in water. The arsenides were prepared by heating niobium and arsenic at 1000°C for 2 days, 720°C for 14 days and quenching in water.

[Ref. 21797]

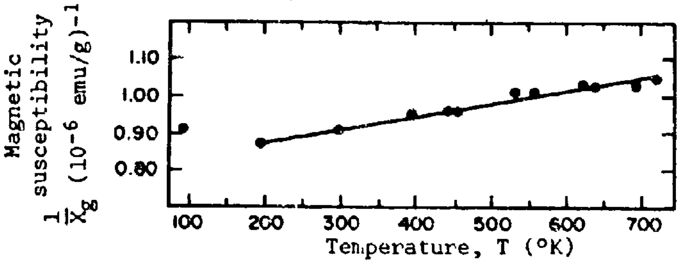
NIOBIUM-SELENIUM

MAGNETIC SUSCEPTIBILITY



Magnetic susceptibility for various niobium selenides and tellurides. These values have not been corrected for induced diamagnetism.

[Ref. 21738]



Reciprocal of the corrected magnetic susceptibility for $NbSe_2$ as a function of temperature.

[Ref. 21738]

NIOBIUM-SELENIUM

SEMICONDUCTING PROPERTIES

Electrical Resistivity ρ (mΩ-cm)	Mobility μ (cm^2/V sec)	Seebeck coefficient S (μV/°C)	Hall coefficient R x 10^{-4} (cm^3/coul)	Notes	Ref.
		NbSe			
5	--	2.7	--	100°C	13958
		$NbSe_2$			
0.18	--	--	--	-196°C	21796*
0.35	--	--	--	25°C	"
--	--	-12.0	--	Polycrystalline 25° - 130°C	"
.5	--	- 1.4	--	100°C	13958
.44	--	- 6.9	--	150° max	"
.58		- 0.2	--	600°C	"
2.04	<10**	-5	<20	Stoich, 300°K	15399
--	8†	--	--	300°K	13958

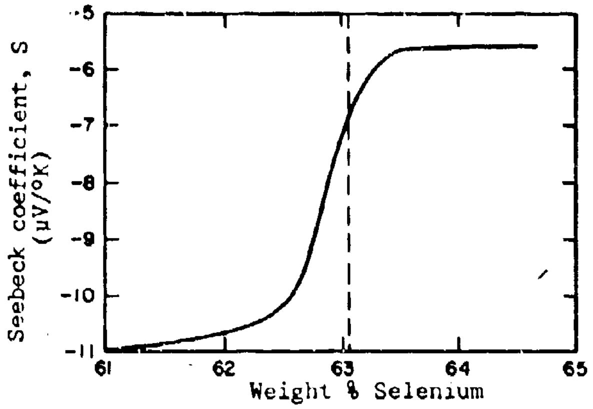
** Thermal conductivity, K = 0.021 w/°C-cm. Figure of merit, Z = 1.96×10^{-5} cm^{-1}

* $n = 3 \times 10^{21}/cm^3$

† $n = 2 \times 10^{21}/cm^3$

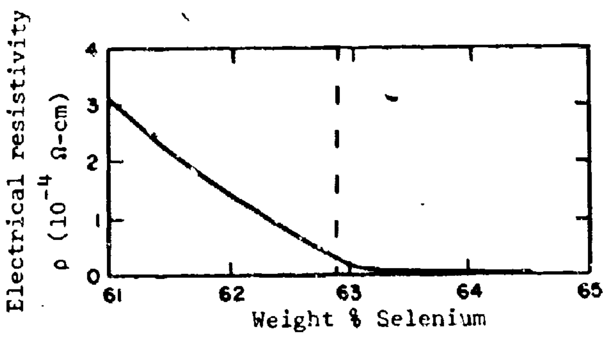
NIOBIUM-SELENIUM

SEMICONDUCTING PROPERTIES



Seebeck coefficient for the niobium selenium system with 61-65 wt.% Se. Data taken at 300°K, sample sintered 16 hours at 900°C. The dashed line represents stoichiometric ratio.

[Ref. 15399]



Electrical resistivity for the niobium selenium system with 61 65 wt.% Se. Data taken at 300°K, sample sintered 16 hours at 900°C. The dashed line represents stoichiometric ratio.

[Ref. 15399]

TECHNETIUM & NIOBIUM-RUTHENIUM

NIOBIUM ALLOYS AND COMPOUNDS

NIOBIUM-MOLYBDENUM, NIOBIUM-TECHNETIUM, AND NIOBIUM-RUTHENIUM SYSTEMS

GENERAL

Nb-Mo In a 1961 article by Hulm and Blaugher [Ref. 12583] the transition temperature of the niobium-molybdenum system was extrapolated to zero near 40 at.% Mo. Since then, work by Hein et al [Ref. 14469] in 1964 has shown that T_c reaches a minimum of 0.016°K at 70 at.% Mo and then rises to 1°K for pure molybdenum. The niobium-molybdenum system shows only the bcc crystal phase.

Nb-Tc The only transition temperature available for the niobium technetium system is given for $NbTc_3$, T_c = 10.5°K, the lattice constant, a_o = 9.625±0.002 [Ref. 12711]. The other data given are for magnetic susceptibility.

Nb-Ru The niobium-ruthenium system is body centered cubic up to 40 at.% ruthenium, takes on a body centered tetragonal to about 55% and remains hexagonal close packed to non-alloyed ruthenium. The transition temperature does not follow this change in phase. At 7.5% Ru, Tc = 4.20°K, falls to <1°K at 20%, and reappears again at 40%, thus ignoring the cubic structure.

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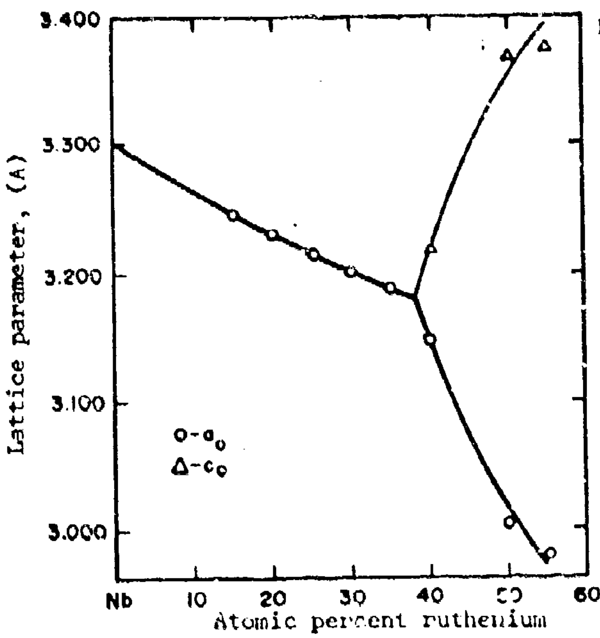
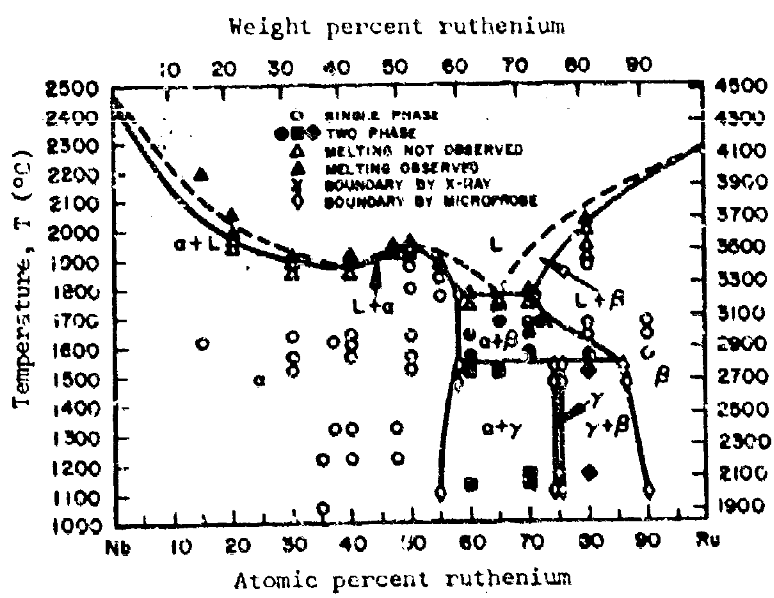
NIOBIUM-RUTHENIUM

GENERAL



Lattice constants for α-niobium-ruthenium alloys. The system is a body centered cubic to 40 at.% ruthenium and body centered tetragonal to about 55 at.% ruthenium. [Ref. 21255]

Nb_3Ru, Cu_3Au type, a_o = 4.207 Å HCl transport method. [Ref. 21843]



Phase diagram for the niobium-ruthenium system.

[Ref. 21255]

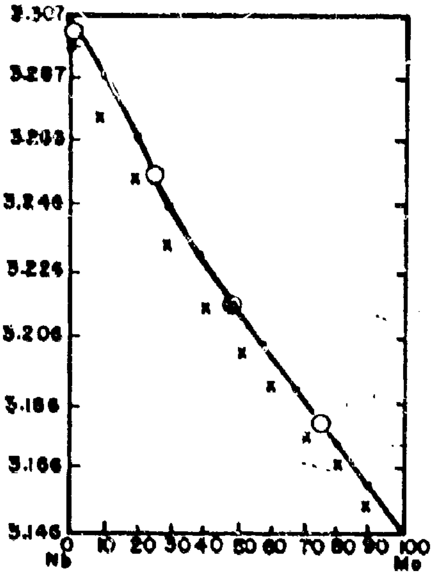
NIOBIUM-MOLYBDENUM

GENERAL

Lattice constants for niobium-molybdenum system as a function of molybdenum content.

[Ref. 19469]

- ● This Ref.
- o Buckle*
- x Eremenko†



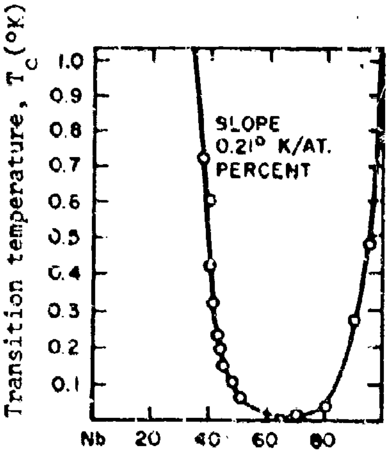
Atomic percent Molybdenum

* Buckle, H. METALLFORSCHUNG, v. 1, no. 53, 1946.

† Eremenko, V. N. UKRAIN. KHEM. ZHUR., v. 20, no. 227, 1954.

NIOBIUM-MOLYBDENUM

TRANSITION TEMPERATURE



Atomic percent Molybdenum

The values plotted here represent the midpoints of the transition region for these alloys. Mo and $Nb_{0.3}Mo_{0.7}$ samples were electron-beam refined, all other samples are from electron-beam refined Mo and Nb, individually melted.

[Ref. 14469]

NIOBIUM-MOLYBDENUM

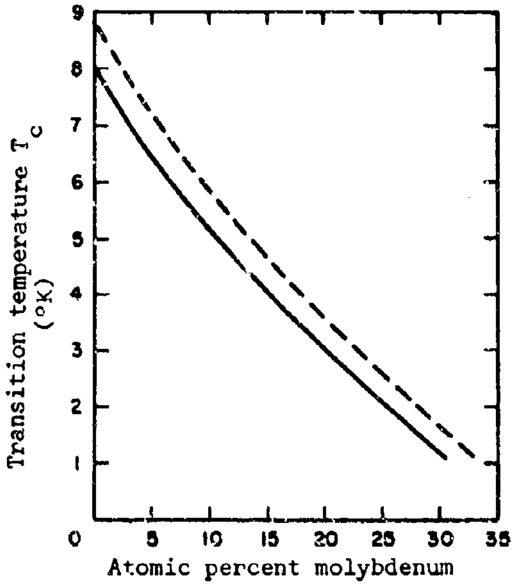
TRANSITION TEMPERATURE

Transition Temperature

At.% Mo	Value (°K) T_c	Sample	Ref.
0	9.17	-	15259
10	5.3	-	7686
25	3.4	-	
38	.76	-	
40	.50	-	
40	.60	Arc melted	15259
42	.31	-	7686
43	.181	-	20520
44	.158	-	
45	.148	-	
48	.108	-	
60	<.05	Arc melted	15259
60	<.03	Formed from electron-beam zone-refined elements.	14469
70	.016	Electron zone-refined after forming.	
80	∿.04	Formed from electron zone-refined elements.	
90	∿.28	-	
100	.945	Electron zone-refined after forming.	

NIOBIUM-MOLYBDENUM

TRANSITION TEMPERATURE



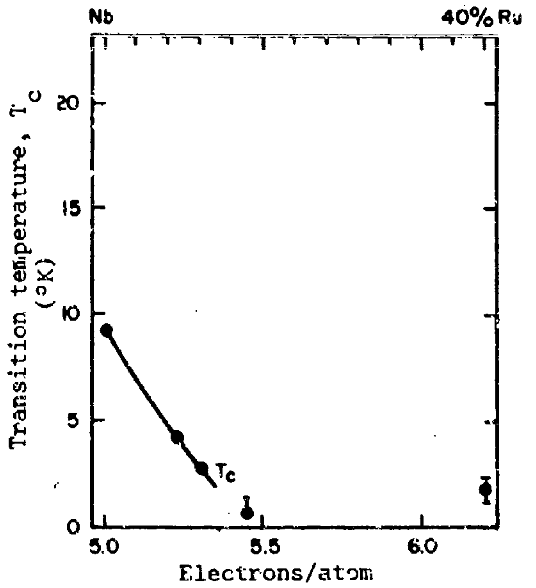
Transition temperature of (Nb-Mo) and $(Nb\text{-}Mo)_{0.99}Fe_{0.01}$ as a function of molybdenum content. [Ref. 11937]

- - - no iron

——— 10% iron

NIOBIUM-RUTHENIUM

Transition temperature for the niobium-ruthenium system to 40 at.% ruthenium. Samples were electron-beam melted at high temperature in less than 10-8mm Hg vacuum. [Ref. 15512]



NIOBIUM-RUTHENIUM

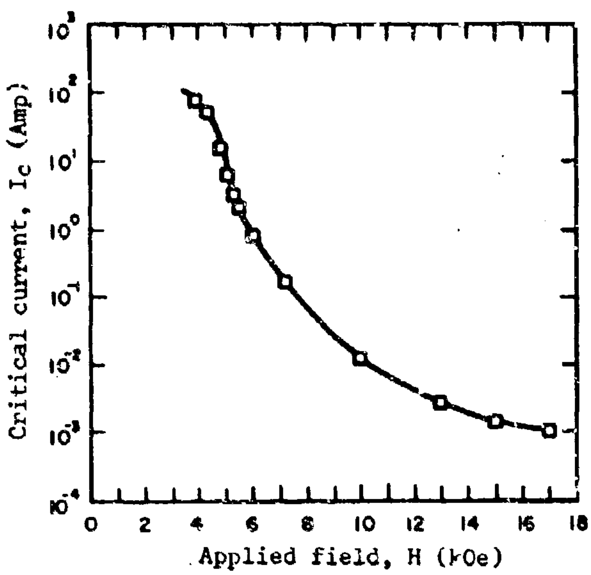
TRANSITION TEMPERATURE

Lattice Constant and Transition Temperature

At.% Ru	Symmetry	Lattice Constant a_o (Å)	c_o (Å)	Transition Temperature T_c (°K)	Notes	Ref.
0	bcc	3.301	-	-	-	21255
7.5		-	-	4.20	-	15512
10		-	-	2.8	-	"
20		3.230	-	-	-	21255
"		-	-	<1	-	15512
30		3.200	-	-	-	21255
"		-	-	<1	-	15512
40	bct	-	-	1.2 ± 2.2	-	"
"		3.147	3.218	-	-	21255
55		2.978	3.378	-	-	"
60		-		2.5	6.8 electrons/atom	9686
71	β hcp	2.762	4.432	-	-	21255
75	γ hcp	2.750	4.418	-	-	
80	β hcp	2.747	4.389	-	-	
100	"	2.706	4.282	-	-	

NIOBIUM-MOLYBDENUM

CRITICAL CURRENT



Critical current for a niobium-molybdenum alloy (1% molybdenum) arc-melted as a function of a transverse applied field.

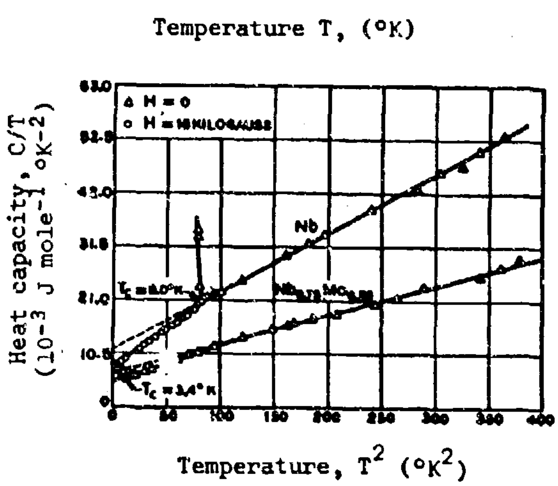
[Ref. 10778]

NIOBIUM- MOLYBDENUM

SPECIFIC HEAT

Heat capacity for niobium and niobium-molybdenum alloy. T_c marks the change in slope of these curves.

[Ref. 7686]

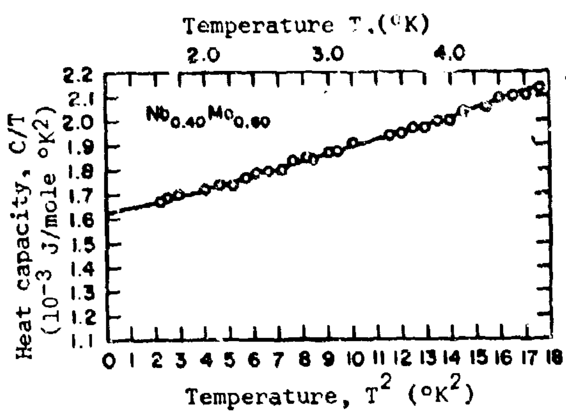


NIOBIUM-MOLYBDENUM

SPECIFIC HEAT

Heat capacity for a niobium-molybdenum alloy ($Nb_{0.40}Mo_{0.60}$) arc-melted and annealed 20 hours at 2000°C in 10^{-5}mm Hg vacuum.

[Ref. 15259]



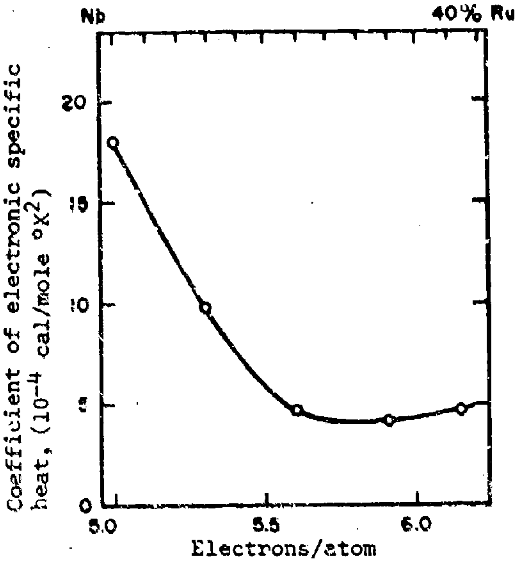
Debye Temperature and Specific Heat

At% Mo	Debye Temperature θ (°K), Measuring Temperature (°K) <9.5	>9.5	1.0-4.2	Coifficient of Electronic Specific Heat γ (10^{-4} J/mole °K^2), Measuring Temperature (°K) <9.5	>9.5	1.0-4.2	Ref.
10	260	290	-	5.88	9.24	-	7686
25	290	320	-	4.54	6.72	-	
38	320	330	-	3.28	3.70	-	
40	-	340	-	-	3.02	-	
"	-	-	371.1	-	-	2.87	15259*
42	-	340	-	-	2.69	-	7686
50	-	380	-	-	2.02	-	"
60	-	-	429.4	-	-	1.62	15259
80	-	405.0	-	-	1.68	-	7686
"	-	-	-	-	-	1.0-2.3	15259

* Samples arc-melted and annealed, 10^{-5}mm Hg vacuum, 20 hr at 2000 °C.

NIOBIUM-RUTHENIUM

SPECIFIC HEAT



Coefficient of electronic specific heat for the niobium-ruthenium system. Samples were electron-beam melted in high vacuum and annealed at high temperature below 10^{-8} mm Hg.

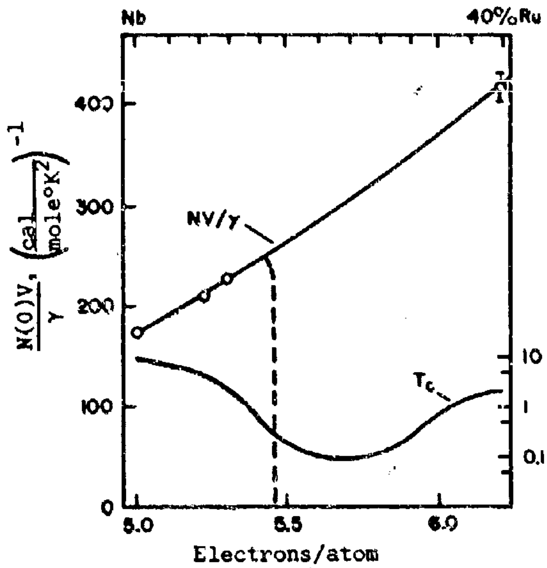
[Ref. 15512]

The expression $\frac{N(0)V}{\gamma}$ is calculated from γ and T_c in the following expression:

$$kT_c = 1.4 \langle h\omega \rangle e^{-1/N(0)V};$$

$\langle h\omega \rangle$ is assumed to be $3/4\ k\theta^2$, θ is the Debye temperature. If T_c is extrapolated linearly to zero, then the dotted line would hold. T_c is calculated.

[Ref. 15512]



NIOBIUM-RUTHENIUM

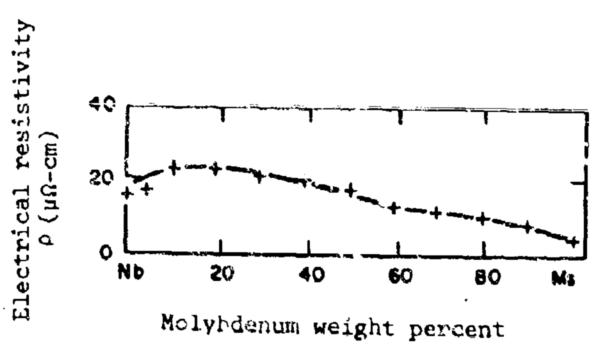
SPECIFIC HEAT

Measured and calculated values used in the graphs on page 156.

At.% Ru	γ (10^{-4} cal/mole °K^2)	θ(°K) (∿4°K)	T_c (°K)	$\frac{N(0)\nu}{\gamma}$ (cal/mole °K^2)$^{-1}$	Ref.
7.5	(11.7)	(290)	4.20	210	15512
10.0	9.7 ± 0.3	304 ± 10	2.6	228 ± 7	
20.0	4.54 ± 0.1	330 ± 10	<1	-	
30.0	3.98 ± 0.04	372 ± 10	<1	-	
38.0	4.45 ± 0.1	405 ± 15	-	-	
40.0	(4.5)	(410)	[illegible].2 ± 2.2	4[illegible]5	

NIOBIUM-MOLYBDENUM

ELECTRICAL RESISTIVITY

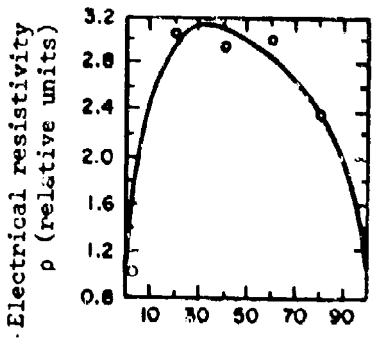


Electrical resistivity in the niobium-molybdenum system, standard sample preparation.

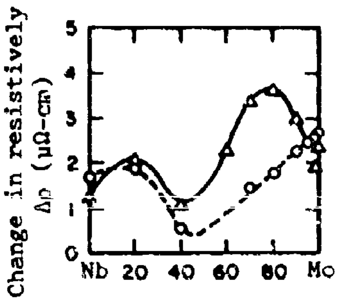
[Ref. 21798]

NIOBIUM-MOLYBDENUM

ELECTRICAL RESISTIVITY



Electrical resistivity for the niobium-molybdenum system at 20°C. [Ref. 21567]



$\Delta\rho$ is the change in resistivity in Nb-Mo system with iron and ruthenium added.

$$\Delta\rho = \rho_{300}\left[\frac{\rho'_{77}/\rho'_{300} - \rho_{77}/\rho_{300}}{1 - \rho'_{77}/\rho'_{300}}\right]$$

(where ρ' and ρ are the resistivities with and without additional components respectively.

___ 1.0% iron

\- - 1.0% ruthenium

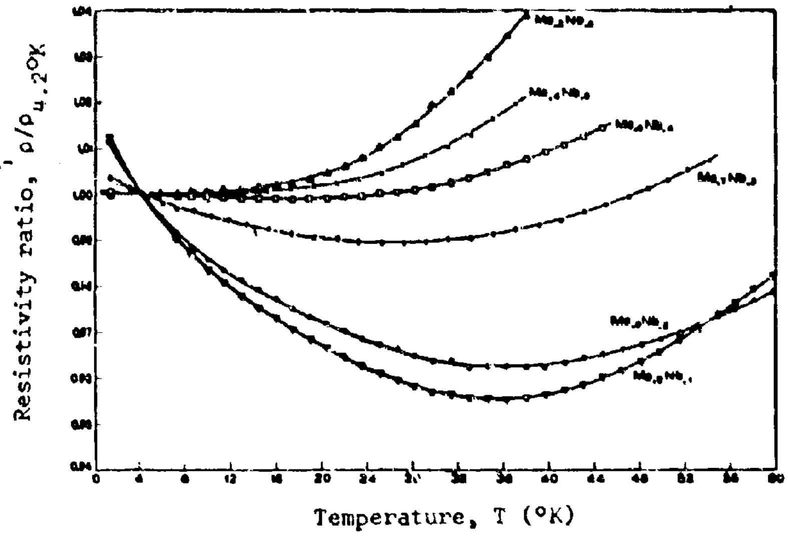
[Ref. 16140]

NIOBIUM-MOLYBDENUM

ELECTRICAL RESISTIVITY

Resistivity as a function of temperature for niobium-molybdenum system with 1 at.% iron added. The samples were arc-melted in an argon atmosphere, and remelted several times to insure homogeneity.

[Ref. 16140]

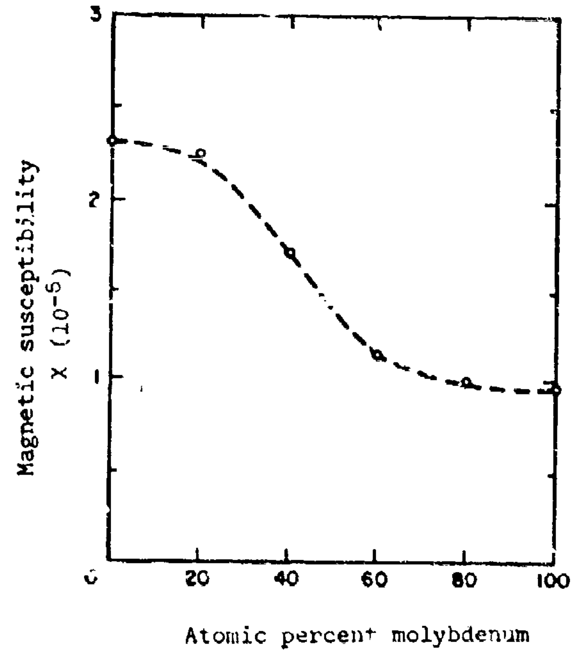


NIOBIUM-MOLYBDENUM

MAGNETIC SUSCEPTIBILITY

Room temperature susceptibility for Nb-Mo with 1% iron added, as a function of the molybdenum content.

[Ref. 11937]



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NIOBIUM-MOLYBDENUM

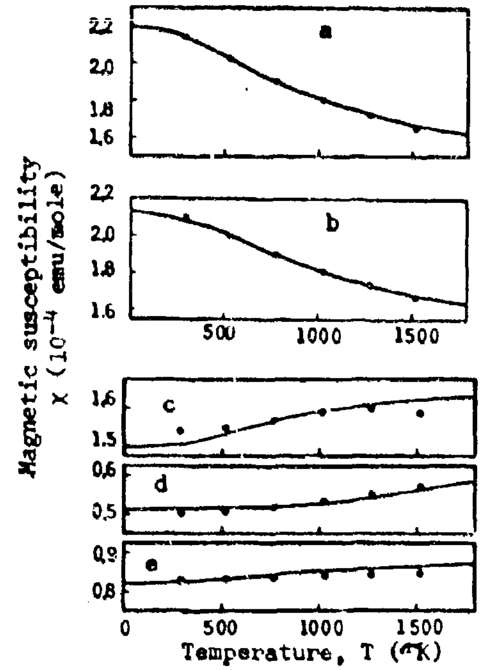
MAGNETIC SUSCEPTIBILITY

Susceptibility for Nb, Mo, and three Nb-Mo alloys.

Orbital susceptibility

		χ_{orb} (10^{-4} emu/mole)
a)	Nb	0.980
b)	$Nb_{.75}Mo_{.25}$	0.980
c)	$Nb_{.50}Mo_{.50}$	1.221
d)	$Nb_{.25}Mo_{.75}$	0.521
e)	Mo	0.544

[Ref. 19617]

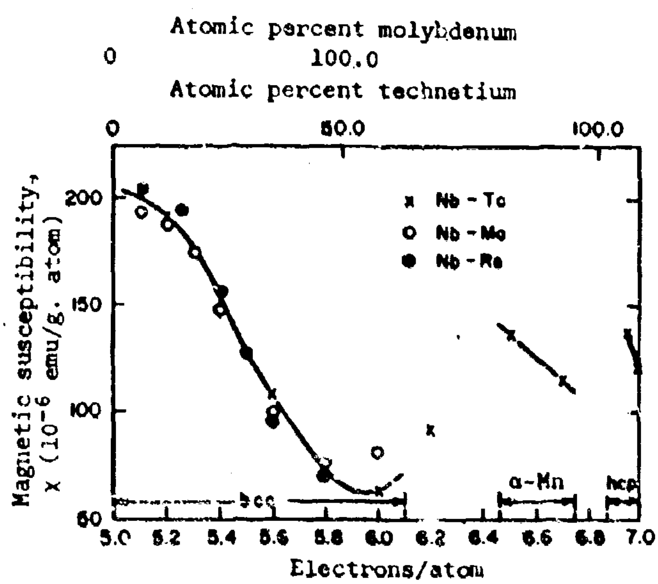


NIOBIUM-MOLYBDENUM AND NIOBIUM-TECHNETIUM

MAGNETIC SUSCEPTIBILITY

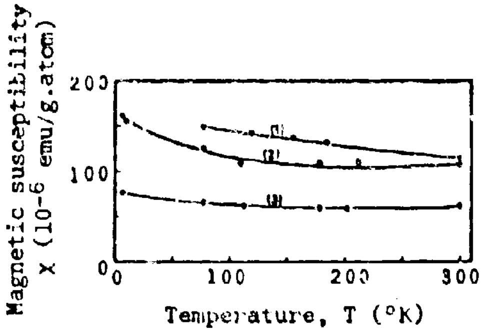
Susceptibility of niobium-technetium and niobium-molybdenum systems. NbTc samples were arc-melted in argon, homogenized 1 week at 1050°C and heat treated 1 week at 700°C. Nb-Re data are given for comparison.

[Ref. 19617]



NIOBIUM-TECHNETIUM

MAGNETIC SUSCEPTIBILITY



Temperature dependence of the susceptibility of three Nb-Tc alloys. The samples were arc-melted in argon, homogenized 1 week at 1050°C and heat treated 1 week at 700°C.

1) $Nb_{.15}Tc_{.85}$
2) $Nb_{.70}Tc_{.30}$
3) $Nb_{.50}Tc_{.50}$

[Ref. 19617]

Lattice Constant and Magnetic Susceptibility

At.% T_c	Symmetry	χ (10^{-6} emu/g.at) (25°C)	Lattice constant (Å) a_o	Lattice constant (Å) c_o
0	bcc	204.4	3.304	-
5		195.8	-	-
10		191.7	3.276	-
20		150.6	3.244	-
30		108.9	3.217	-
40		73.4	3.192	-
50		63.3	3.170	-
60	bcc+α Mn	91.7	3.159	-
75	α Mn	136.5	-	-
85	"	114.8	9.547	-
97	hcp	138.3	-	-
100	"	120.8	2.743	4.400

[Ref. 19617]

NIOBIUM-RUTHENIUM

MAGNETIC SUSCEPTIBILITY

Magnetic Susceptibility

	Value	At.% Ru	Notes	Ref.
χ_{tot}*	176×10^{-6} emu/g.at.	10	5.3 electrons/atom, A 2 type/structure.	14464
χ_{add}	140×10^{-6} emu/g.at.	"	" "	"
χ	60×10^{-6} cm^3/g	60	6.8 electrons/atom, sample cooled from 1300°C.	9686
χ_{at}	$5900 \times 10^{-6} cm^3$/mole	"	" "	"

* $\chi_{tot} = \chi_{ion} + \chi_{pauli} + \chi_{L.P.} + \chi_{add}$

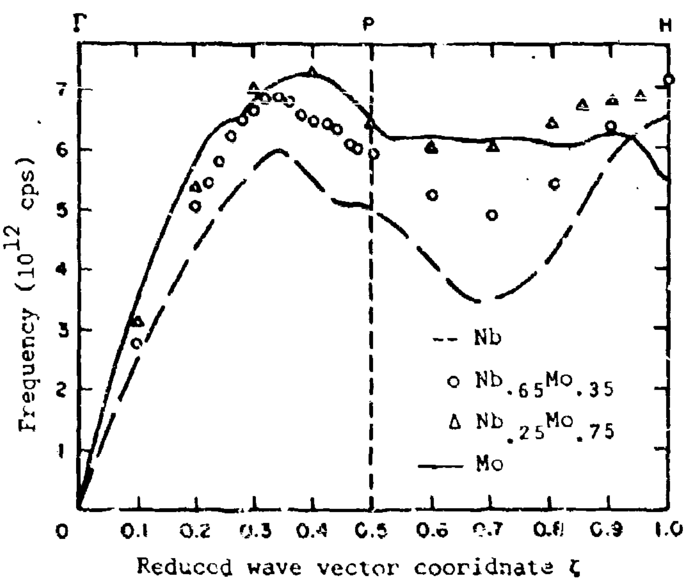
χ_{tot} is taken as the sum of the various susceptibility contributions. The authors state that χ_{add} is probably due to the orbital paramagnetism.

NIOBIUM-MOLYBDENUM

PHONON DISPERSION

The Λ_1 branch of the measured phonon dispersion curves of Mo, Nb and two Nb-Mo alloys. The neutron scattering measurements were made at 300°K.

[Ref. 21842]



SECTION 5
NIOBIUM RHODIUM & NIOBIUM PALLADIUM SYSTEMS

NIOBIUM-RHODIUM AND NIOBIUM-PALLADIUM

GENERAL

Nb-Rh The niobium-rhodium system is very complicated, showing nine different phases. The tetragonal (40% Rh) has the highest transition temperature ~[illegible].0°K; while β-tungsten, Nb_3Rh, has a T_c of only ~2.5°K. Zegler [Ref. 18750] has alloyed Nb_3Rh with other elements; the lattice constants and transition temperatures for these ternary alloys are given.

Nb-Pd The niobium-palladium system has a transition temperature of about 2°K at a composition of 40 at.% palladium. The only other niobium-palladium data available were in the palladium-rich region. The following values are taken from this Zwingman paper [Ref. 21799].

Property	Symbol	Value	
Change in resistivity	$\Delta\rho/a$*	2.96	(μΩ-cm/at.%)
Change in thermolectric effect	$\Delta\varepsilon/a$	+[illegible].6	(μV/°C-at.%)
Change in temperature coefficient of resistivity	$\Delta\alpha/a$	-1.35	(10^{-3}/°C-at.%)

* a is atomic percent niobium

The coefficient of electronic specific heat and Debye temperature are given for 40 at.% palladium: $\gamma=7.13\pm0.08 \times 10^{-4}$ cal/°K^2 mole; and $\Theta=333\pm5$°K [Ref. 15323].

NIOBIUM-RHODIUM

TRANSITION TEMPERATURE

Lattice Constant and Transition Temperature

At% Rh	Symmetry	Phase	Lattice Constants a_o	b_o	c_o	Transition Temperature T_c	Notes	Ref.
12	cubic	αNb	3.265±0.002	-	-	-	-	21253
18.5	cubic	αNb	3.245±0.002	-	-	-	-	
24.8	cubic	αNb_3Rh	5.120±0.003	-	-	-	-	
25.0*	cubic	αNb_3Rh	5.1317	-	-	2.64	-	18750
25.0	cubic	αNb_3Rh	5.115	-	-	2.5	-	9620
29.7	tetragonal	σ	9.869±0.004	-	5.106±0.003	-	-	21253
40.0	"	"	9.80	-	5.07	4.04±0.2	6.6 electrons/atom	9868
40.0	"	"	-	-	-	4.1	-	7648
51.3	tetragonal	α2	4.019±0.004	-	3.809±0.004	-	-	21253
55.9	ortho-rhombic	α3	2.827±0.002	4.770±0.005	13.587±0.010	-	-	
58.8	" "	α4	2.813±0.002	4.808±0.005	4.510±0.005	-	-	
62.3	monoclinic	α5	2.806±0.002	4.772±0.003	20.25 ±0.10	-	α=90° 31.5'	
69.2	hexagonal	α6	5.483±0.003	-	13.405±0.005	-	-	
74.5	cubic	$\alpha NbRh_3$	3.857±0.002	-	-	-	-	
89.1	"	αRh	3.835±0.002	-	-	-	-	

* Nb_3Rh, Cu_3Au type, a_o=4.207 Å. Sample preparations, HCl transport method [Ref. 21843]

NIOBIUM-PALLADIUM

TRANSITION TEMPERATURE

Transition Temperature

At.% Pd	Transition Temperature T_c(°K)	ΔT*	Symmetry	Notes	Ref.
40†	1.7	-	α-Mn	-	15323
"	2.04	0.1	"	Cooled from 1000°C 7.00 electrons/atom.	9686
"	2.47	0.4	"	Cooled from melting point, 7.00 electrons/atom.	"

* ΔT is w.th width of the transition region.

† Nb_3Pd, 25% Pd, Cu_3Au type, A_o = 4.207 Å, sample prepared by HCl transport method.

[Ref. 21843]

NIOBIUM-RHODIUM-M

TRANSITION TEMPERATURE

Lattice Constants and Transition Temperature: $Nb_3Rh_{1-x}M_x$

M	x	Lattice constant a_o Å	Transition Temperature T_c
Co	.02	5.132	2.28
	.05	5.135	1.96
	.10	5.1347	1.90†
Ru	.02	5.132	2.42
	.05	5.135	2.42
	.10	5.1346	2.44†
Pd	.02	5.133	2.50
	.05	5.134	2.49
	.10	5.1345	2.55†

† three phase alloys

[Ref. 18750]

NIOBIUM-RHODIUM-M

TRANSITION TEMPERATURE

Lattice Constants and Transition Temperatures
(Continued)

M	x	Lattice constant a_o Å	Transition Temperature T_c
Os	.02	5.134	2.42
	.05	5.132	2.39
	.10	5.1302	2.30
	.30	5.1315	< 1.7
	.50	5.1334	< 1.7
	.70	5.1345	< 1.7
	.90	5.1354	< 1.7
Ir	.02	5.131	2.43
	.05	5.132	2.38
	.10	5.1329	< 1.7
	.30	5.1340	< 1.7
	.50	5.1349	< 1.7
	.70	5.1349	< 1.7
	.90	5.1345	< 1.7
Pt	.02	5.132	2.52
	.05	5.133	2.53
	.10	5.1336	2.8
	.30	5.1395	5.1
	.50	5.1450	6.25
	.70	5.1487	7.4
	.90	5.1534	7.9
	.95	5.160	8.3
	.98	5.157	9.6
Au	.02	5.133	2.53
	.05	5.137	2.52
	.10	5.1412	2.70
	.30	5.1573	4.6
	.50	5.1688	6.6
	.70	5.1827	9.5
	.90	5.1960	10.8
	.95	5.200	11.0
	.98	5.203	10.9

[Ref. 18750]

NIOBIUM-RHODIUM AND NIOBIUM-PALLADIUM

MAGNETIC SUSCEPTIBILITY

Magnetic Susceptibility

System	χ_{tot}*(10^{-6} emu/g.at)	χ_{add}(10^{-6} emu/g.at)	$\chi^{\dagger}$(10^{-6} cm^3/g)	χ_{at}(10^{-6} cm^3/g)	χ(10^{-6})**	Symmetry
$Nb_{.60}Rh_{.40}$	79	49	82	7900	810	σ, $D8_b$
$Nb_{.60}Pd_{.40}$	50	29	50	5000	520	α-Mn

* $\chi_{tot} = \chi_{ion} + \chi_{Pauli} + \chi_{L.P.} + \chi_{add}$ [Ref. 14464]

$\chi_{L.P.}$ (Landau-Peierls) electronic specific heat contribution

† $Nb_{.60}Rh_{.40}$ colled from 1000°C and $Nb_{.60}Pd_{.40}$ cooled from the melting point [Ref. 9686]

** Volume susceptibility, 300°K

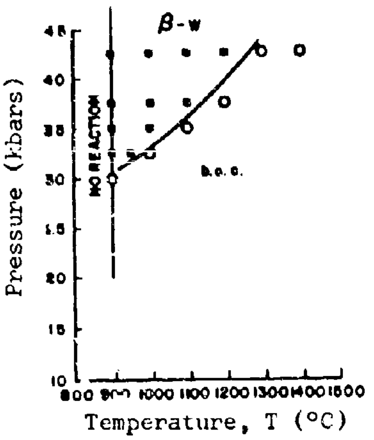
SECTION 5
NIOBIUM-INDIUM SYSTEM

NIOBIUM ALLOYS AND COMPOUNDS

NIOBIUM-INDIUM SYSTEM

GENERAL

Niobium and indium (Nb_3In) show the β-tungsten structure under high pressure, 40-70 kbars, and at an optimum temperature of 1[illegible]00°C. The lattice constant for this material is given by Banus et al [Ref. 12280] as 5.303 ± 0.003 Å and the transition temperature is given as 9.2°K.



Pressure-temperature phase diagram
for Nb_3In.

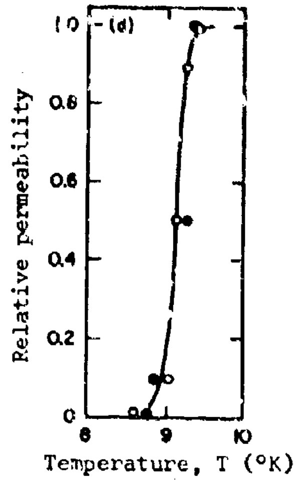
□ β-tungsten

○ bcc

[Ref. 17303]

NIOBIUM-INDIUM

TRANSITION TEMPERATURE

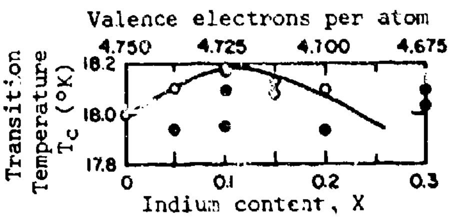


Transition curve for β-tungsten Nb In formed under high pressure conditions.

[Ref. 12280]

NIOBIUM-INDIUM-TIN

TRANSITION TEMPERATURE



Transition temperature as a function of indium content, $Nb_3In_xSn_{1-x}$.

• Sintered once

o Sintered twice

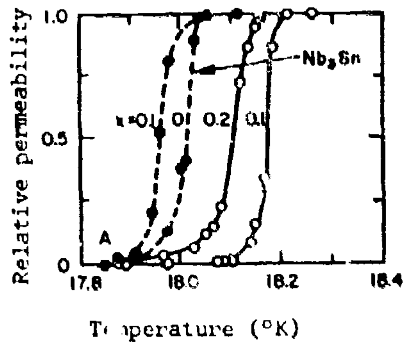
[Ref. 10749]

NIOBIUM-INDIUM-TIN

TRANSITION TEMPERATURE

Transition curves for β-tungsten $Nb_3In_xSn_{1-x}$ sintered 6 hours at 1200°C:

- ● sintered once
- o sintered twice



[Ref. 10749]

NIOBIUM-INDIUM-M

TRANSITION TEMPERATURE

Compound	Transition Temperature T_c °K	Notes	Ref.
$Nb_3In_{0.5}Zr_{0.5}$	6.4	-	10784
Nb_6InSb	4.2-6.2	samples prepared by HCl transport method	21843
Nb_6InAs	7.2-7.4	"	"

SECTION 5
NIOBIUM-ANTIMONY & NIOBIUM-TELLURIUM SYSTEMS

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NIOBIUM ALLOYS AND COMPOUNDS

NIOBIUM-ANTIMONY AND NIOBIUM-TELLURIUM SYSTEMS

GENERAL

Nb-Sb Niobium antimonide (Nb_3Sb) has a predominant β-tungsten crystalline phase, with small amount of other phases present and shows no T_c>1.02°K [Ref. 14387]. These other phases finally disappear and T_c rises when the antimony is replaced with an alloying agent such as tin. $Nb_3Sb_xSn_{1-x}$ shows a single phase β-tungsten structure.

Nb-Te The niobium tellurium system does not show a transition temperature. The data are given for this system as an n type semiconductor.

NIOBIUM-ANTIMONY

GENERAL

Lattice Constant

Formula	At.% Sb	Crystallography	Lattice Constants (Å) a_o	b_o	c_o	β	Ref.
Nb_3Sb	25	β-tungsten	5.263	-	-	-	19559
$NbSb_2$	67	monoclinic	10.239	3.6319	8.333	120.07°	-

* Furuseth, Sigrid & Arne Kjekshus, ACTA CRYST., v. 18, p. 320, 1965.

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NIOBIUM-ANTIMONY-M

TRANSITION TEMPERATURE

Lattice Constant and Transition Temperature

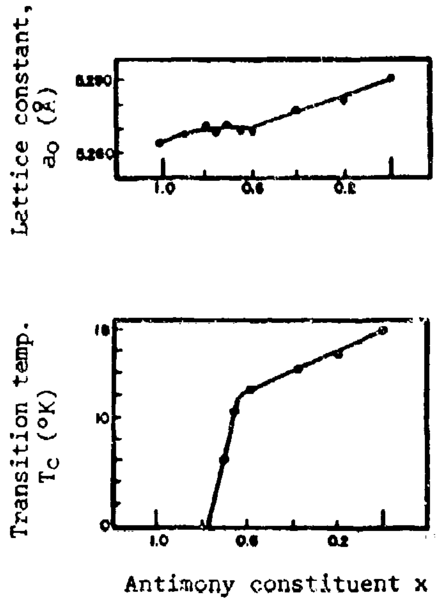
Formula	Lattice Constant (Å) a_o	Lattice Constant (Å) c_o	Transition Temperature T_c °K	Notes	Ref.
Nb_3Sb	5.263	-	<1.02*	-	19559
$Nb_3Sb_{>.7}Al_{<.3}$	-	-	<4.2	-	
$Nb_3Sb_{.7}Al_{.3}$	-	-	7.7	-	
Nb_3Al	5.183	-	15.7	-	
$Nb_3Sb_{.9}Sn$	5.267	-	-	-	13155
$Nb_3Sb_{\sim.8}Sn_{\sim.2}$	-	-	0	Powders, 16 hrs. 1200°C	19614
$Nb_3Sb_{.8}Sn_{.2}$	5.270	-	-	-	13155
$Nb_3Sb_{.75}Sn_{.25}$	5.268	-	<5.0	-	
$Nb_3Sb_{.7}Sn_{.3}$	5.270	-	6.8	-	
$Nb_3Sb_{.65}Sn_{.35}$	5.268	-	10.5	-	
$Nb_3Sb_{.6}Sn_{.4}$	"	-	12.4	-	
$Nb_3Sb_{.4}Sn_{.6}$	5.273	-	15.8	-	
"	-	-	12.0	Powders, 16 hrs. 1200°C	19614
$Nb_3Sb_{.2}Sn_{.8}$	5.283	-	18.0	-	13155
Nb_3Sn	5.292	-	"	-	"

* [Ref. 14387]

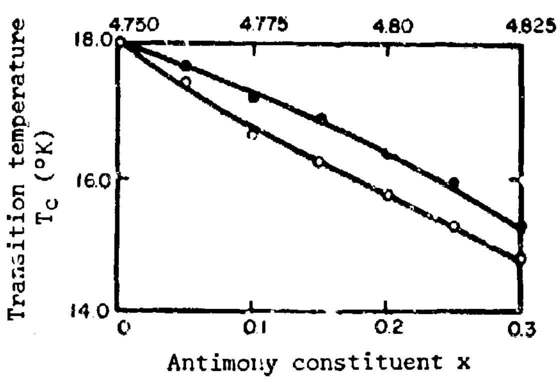
NIOBIUM-ANTIMONY-TIN

TRANSITION TEMPERATURE

Lattice constants and transition temperature for $Nb_3Sb_xSn_{1-x}$ as a function of composition. Powdered samples were fired at 1200°C for 66 hours.



[Ref. 13155]



Transition temperature of $Nb_3Sb_xSn_{1-x}$ as a function of antimony constituent, powder pressed to 8 tons/cm^2 sintered 6 hours at 1200°C.

o) inductive measurement

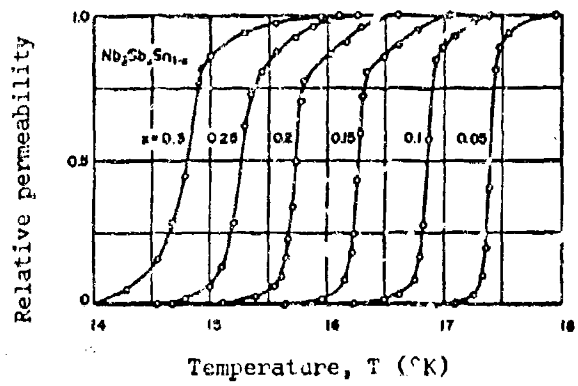
•) resistive measurement

[Ref. 15343]

NIOBIUM-ANTIMONY-TIN

TRANSITION TEMPERATURE

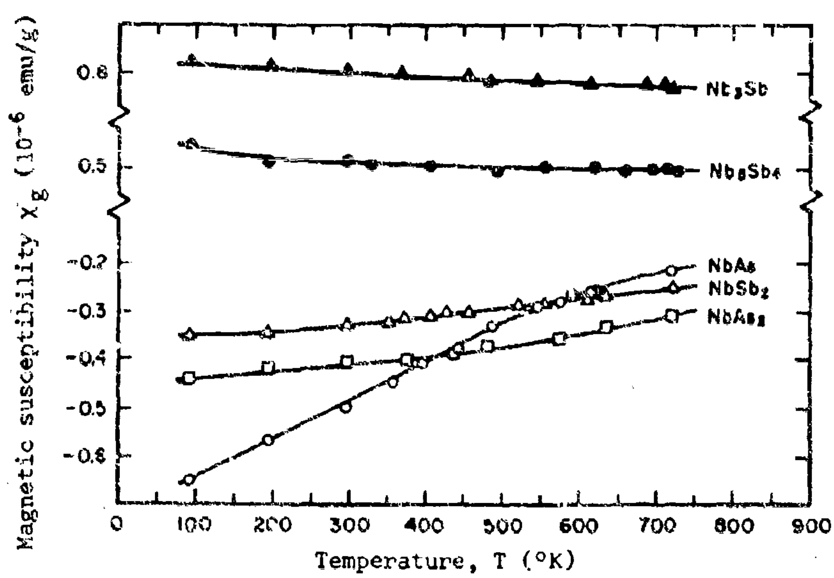
Transition curves of $Nb_3Sb_xSn_{1-x}$ as a function of the temperature with different amounts of antimony.



[Ref. 15343]

NIOBIUM-ANTIMONY

MAGNETIC SUSCEPTIBILITY



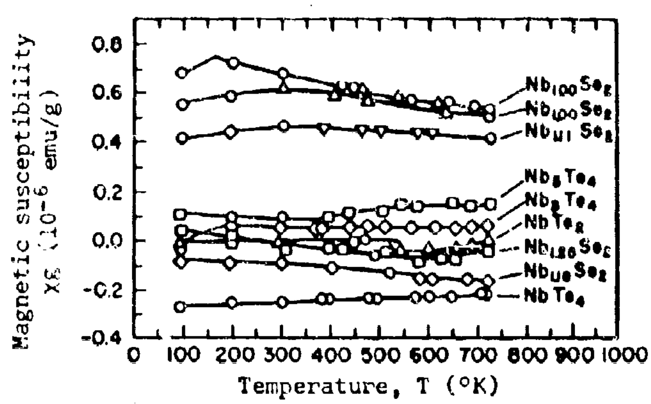
Magnetic susceptibility for niobium antimonides and arsenides as a function of temperature. The antimonides were prepared by heating niobium and antimony at 1000°C for 2 days, 800°C for 14 days and quenching in water. The arsenides were prepared by heating niobium and arsenic at 1000°C for 2 days, 720°C for 14 days and quenching in water.

[Ref. 21797]

NIOBIUM-TELLURIUM

MAGNETIC SUSCEPTIBILITY

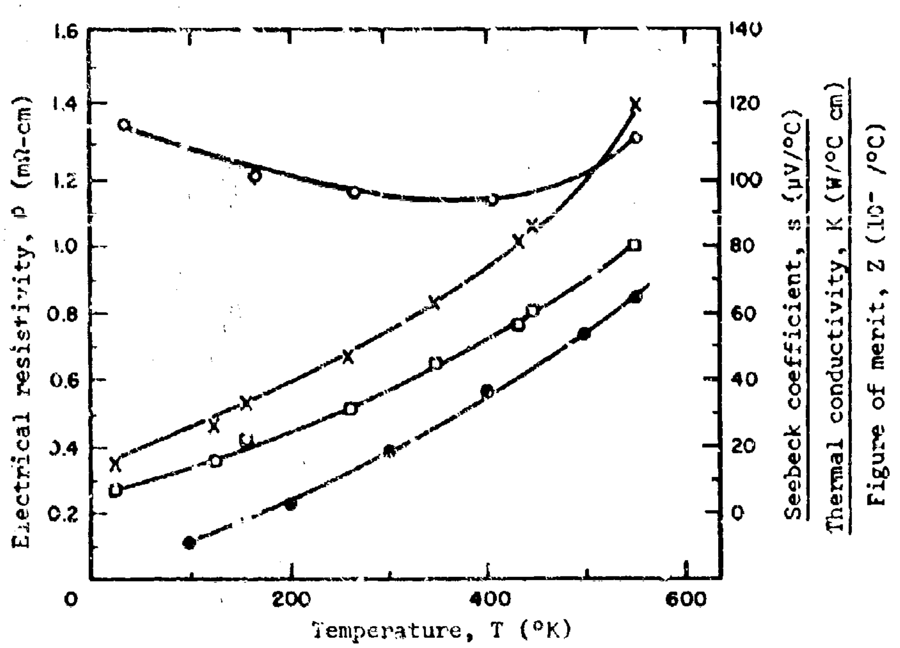
Magnetic susceptibility for various niobium selenides and tellurides. These values have not been corrected for induced diamagnetism.



[Ref. 21738]

NIOBIUM-TELLURIUM

ELECTRICAL RESISTIVITY



Thermoelectric properties of $NbTe_2$ as a function of temperature single crystals were prepared by vapor transport from polycrystalline niobium telluride.

[Ref. 21796]

NIOBIUM-TELLURIUM

SEMICONDUCTING PROPERTIES

Semiconducting Properties

Formula	Lattice constant Å a_o	c_o	Electrical Resistivity $\rho(10^{-4}\ \Omega\text{-cm})$		Seebeck coefficient S (μV/°C)		Thermal conductivity K (W/°C-cm)	Figure of merit Z ($°C^{-1}x10^{-5}$) 25°C	Symmetry	Ref.
NbTe	-	-	4.8[a]	2.6[b]	4.7[a]	14.2[b]	-	.0078	-	13958
NbTe	10.904	20.119	-	-	-		-	-	rhom.	21796
$NbTe_2$	"	19.888	0.26[c]	0.077[d]	15		0.019	4.55	"	"
Nb_3Te_4	10.671	3.6468	-	-	-		-	-	hex.	*
$NbTe_4$	2x6.499	3x6.837	-	-	-		-	-	"	21258

a) 100°C, b) 600°C, d) 25°C, e) - 196°C

* Selte, Kan and Arne Kjekshus, ACTA. CHEM. SCAND., v. 18, p. 690, 1964.

SECTION 6
NIOBIUM-HAFNIUM, NIOBIUM-TANTALUM & NIOBIUM-TUNGSTEN SYSTEMS

NIOBIUM ALLOYS AND COMPOUNDS

NIOBIUM-HAFNIUM, NIOBIUM-TANTALUM AND NIOBIUM-TUNGSTEN SYSTEMS

GENERAL

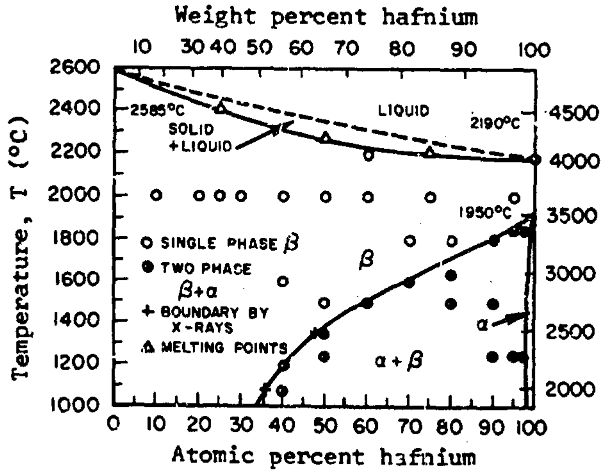
Nb-Hf Niobium-hafnium alloys show a transition temperature near that of pure niobium until the hafnium content approaches 70 at.%. In region>70 at.% hafnium, Hf is found with the bcc Nb-Hf solid solution and T_c data are not available.

Nb-Ta The niobium-tantalum system comprises a series of solid solutions with the lattice constant nearly the same throughout. The transition temperature for this system decreases from about 9°K for niobium to about 4.5°K for tantalum.

Nb-W Niobium and tungsten form a series of solid solutions throughout the system. The lattice parameters are given to about 25% tungsten content and transition temperatures are given to about 40% tungsten content.

NIOBIUM-HAFNIUM

GENERAL

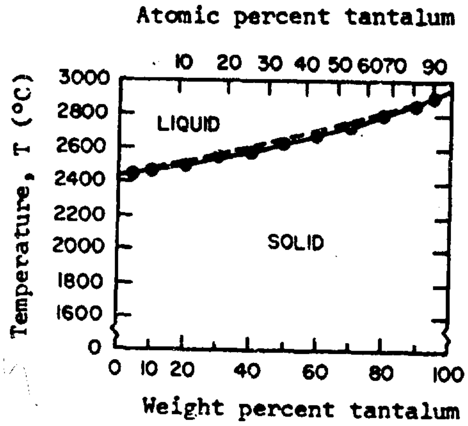


Tentative phase diagram for the niobium-hafnium system.

[Ref. 21732]

NIOBIUM-TANTALUM

GENERAL



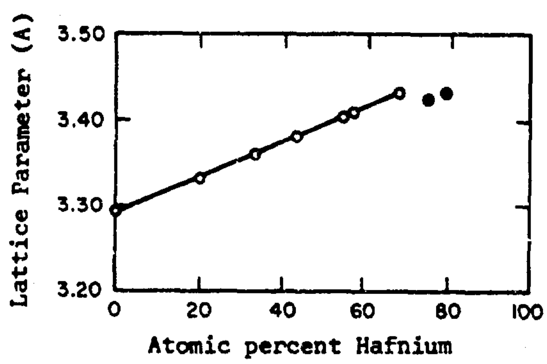
Phase diagram for the niobium-tantalum system.

[Ref. 21262]

NIOBIUM-HAFNIUM

GENERAL

Lattice parameter for niobium-hafnium system as a function of hafnium content. Samples melted in a helium arc furnace and homogenized for 48 hours at 1000°C.



° bcc

• bcc Nb-Hf + hcp Hf

[Ref. 20160]

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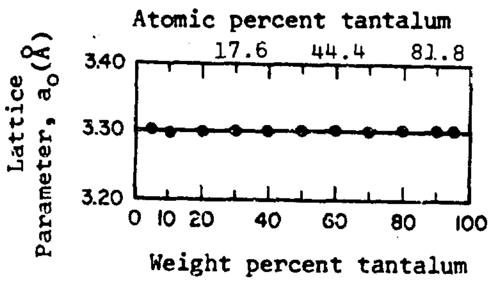
NIOBIUM-TANTALUM

GENERAL



*Donnay, J., ed. CRYSTAL DATA: DETERMINATIVE TABLES. 2d. ed. New York, American Crystallographic Assoc., 1963. p. 829.

Lattice parameter for niobium-tantalum system.

Lattice Constants

Nb, a_o = 3.302 Å *

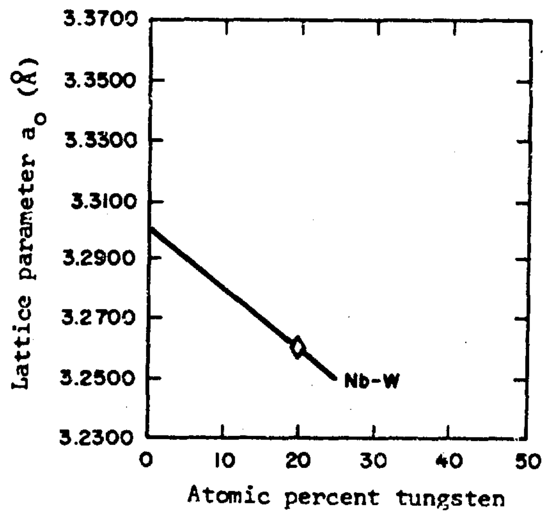
Ta, a_o = 3.3026 Å *

[Ref. 21262]

NIOBIUM-TUNGSTEN

GENERAL

Lattice parameter for niobium-tungsten system as a function of tungsten content. Standard sample preparation.



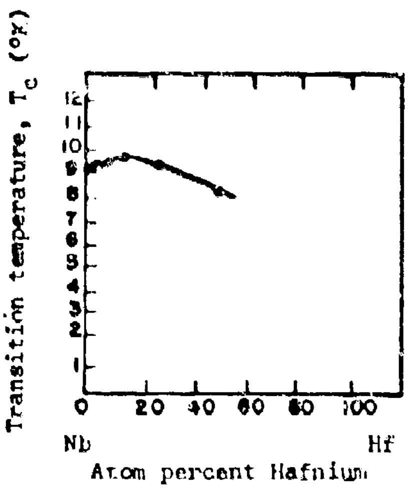
[Ref. 10778]

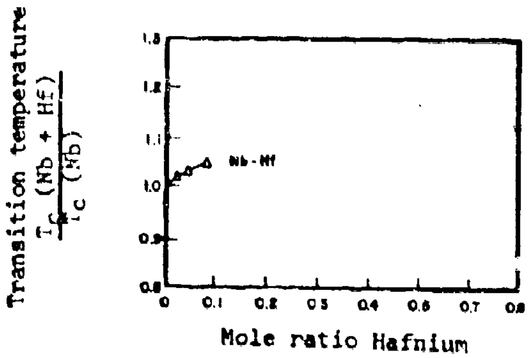
NIOBIUM-HAFNIUM

TRANSITION TEMPERATURE

Transition temperature of niobium-hafnium system as a function of hafnium content.

[Ref. 21583]





Transition temperature of niobium-hafnium system as a function of hafnium content. Standard methods of sample preparation.

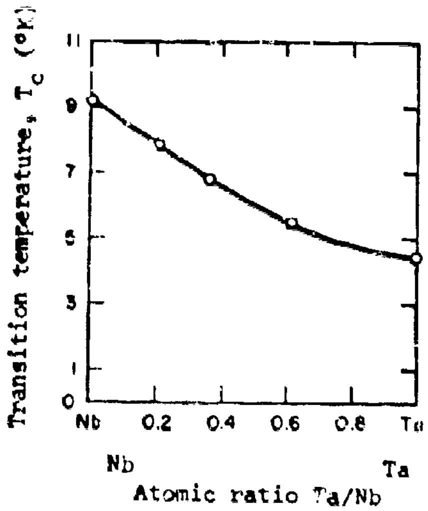
[Ref. 10778]

NIOBIUM-TANTALUM

TRANSITION TEMPERATURE

Transition temperatures for niobium-tantalum system. The sample preparations were standard.

[Ref. 12583]

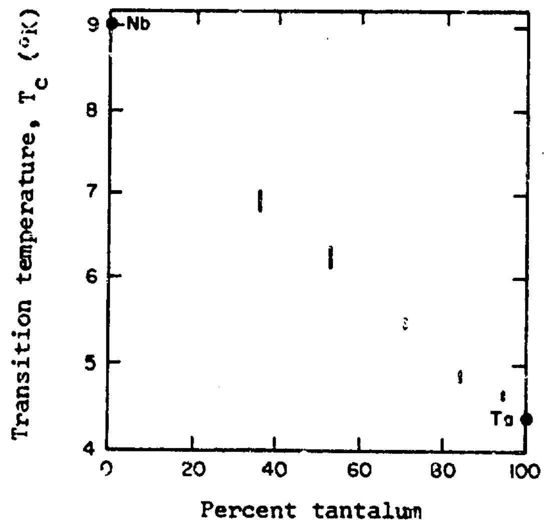


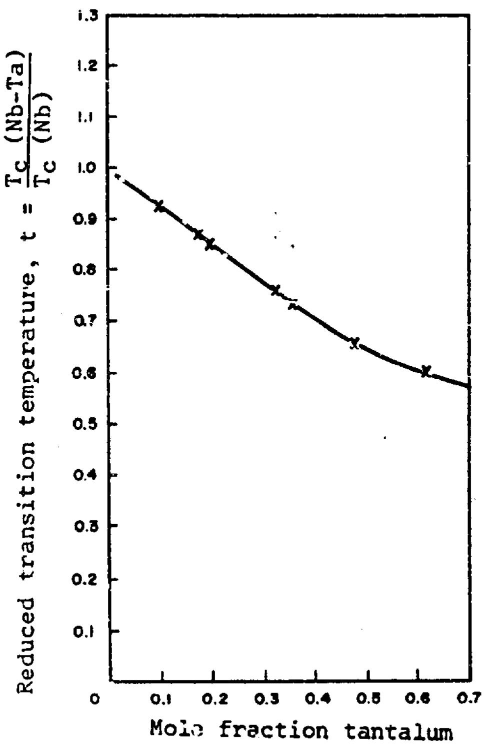
NIOBIUM-TANTALUM

TRANSITION TEMPERATURE

Transition temperatures for the niobium-tantalum system. Powders were pressed into a rod and melted by the floating zone process, after swaging, further zone-melting produced a single crystal.

[Ref. 12452]



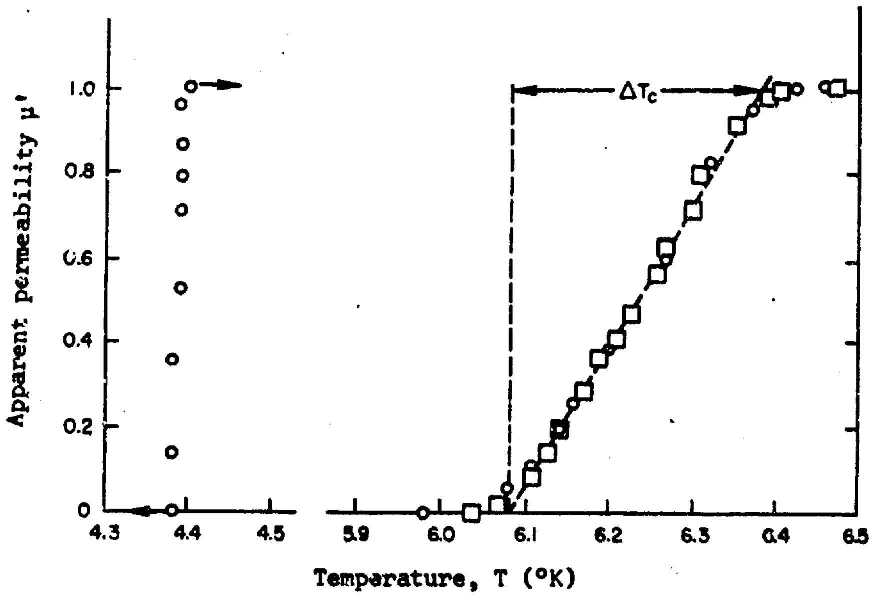


Reduced transition temperatures for niobium-tantalum system.

[Ref. 10778]

NIOBIUM-TANTALUM

TRANSITION TEMPERATURE



Transition curve for two $Nb_{.47}Ta_{.53}$ samples. The data were taken in a small alternating field of about 15 kc, on thin rods with a length to diameter ratio of 15.

	O	□
Trapped flux	10%	0%
hardness (dhp)	122	76

$\mu' = \frac{V - V_s}{V_n - V_s}$, where V is measured voltage and V_n & V_s are the secondary coil voltages in the normal and superconducting states respectively.

[Ref. 12452]

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NIOBIUM-TUNGSTEN

TRANSITION TEMPERATURE

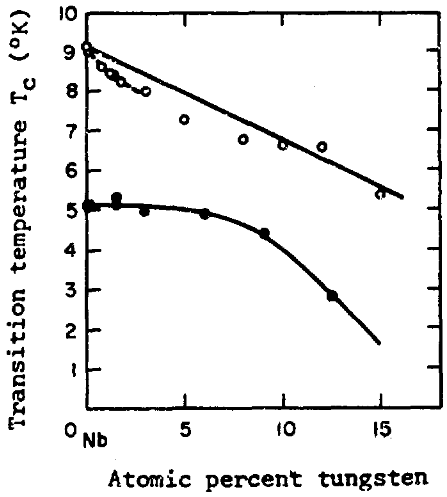
Transition temperature as a function of tungsten content for a niobium-tungsten system.

Initial Material

o Zone refined Nb

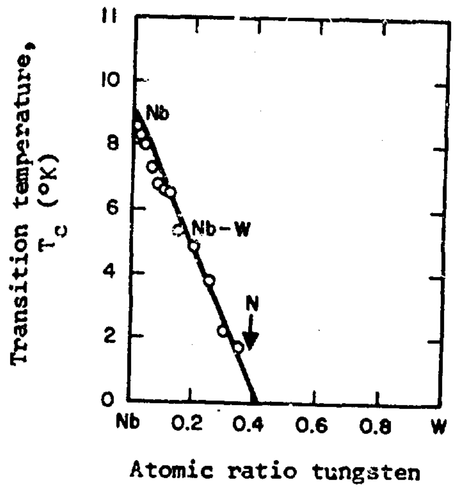
● Powdered Nb

[Ref. 12583]



Transition temperature for niobium-tungsten system.

[Ref. 12583]

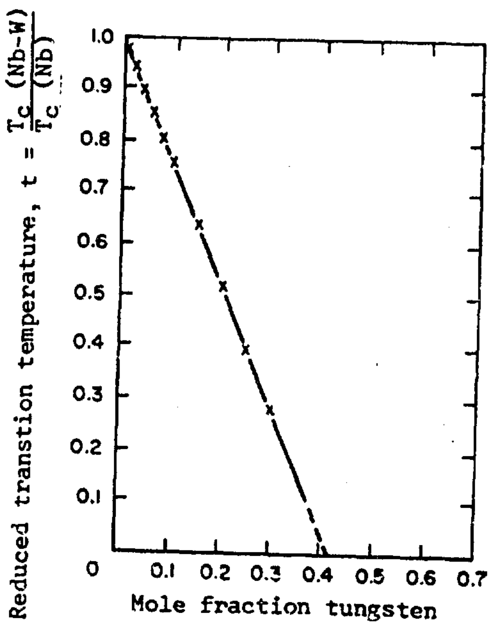


NIOBIUM-TUNGSTEN

TRANSITION TEMPERATURE

Reduced transition temperature for the niobium-tungsten system.

[Ref. 10778]



NIOBIUM-TANTALUM

PENETRATION DEPTH AND COHERENCE LENGTH

System	Penetration depth $\lambda(0)$ (Å)	Coherence length ξ (Å)	Ref.
$Nb_{.64}Ta_{.36}$	890	~142	19930
$Nb_{.47}Ta_{.53}$	-	125	"
"	-	250	21800

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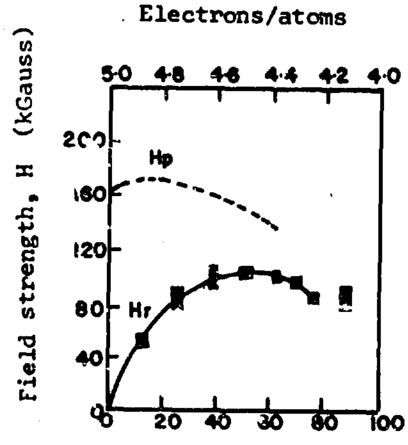
NIOBIUM-HAFNIUM

CRITICAL FIELD



Critical fields for niobium-hafnium alloys as a function of hafnium content, J = 10 (Amp/cm^2) T = 0.2°K. Standard sample preparation. Hp is the upper limit of the critical field transition range and is defined:

$$H_p = (e_o/\sqrt{2}\mu_B)\,[1-(T/T_c)^2]$$

The H_r value is used to denote (1) the field at which resistance is first measured, and (2) the field at which full resistance is restored. The rectangles in the above figure and the two values in the following tables show these H_r values.

[Ref. 11924]

Critical Field Strength

Symbol	Values (kGauss) (1)	Values (kGauss) (2)	at.% Hf	Symmetry	Notes	Ref.
H_r	62.1	69.6	12.5	bcc	arc-melted	11924
	78.9	89.6	25.0		J = 10 amp/cm^2	
	91.0	101.6	37.5		T_c = 1.2°K	
	102.4	109.4	50.0			
	99.5	103.5	62.5			
	95.1	98.8	70.0			
	83.1	89.7	75.0			
	83.0	96.0	87.5	hcp + bcc		

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NIOBIUM-HAFNIUM

TRANSITION TEMPERATURE AND CRITICAL FIELD

Compound	Transition temperature T_c(°K)	Electrical resistivity ρ_n(4.2°K) (μΩ-cm)	H_{ps}* (4.2°K) (kGauss)	H_u† (4.2°K) (kGauss)	Sample
$Nb_{.25}Hf_{.75}$	>4.2	124	15	>26	arc-cast
$Nb_{.25}Hf_{.75}$	>4.2	124	17	>28	cold rolled, 2:1

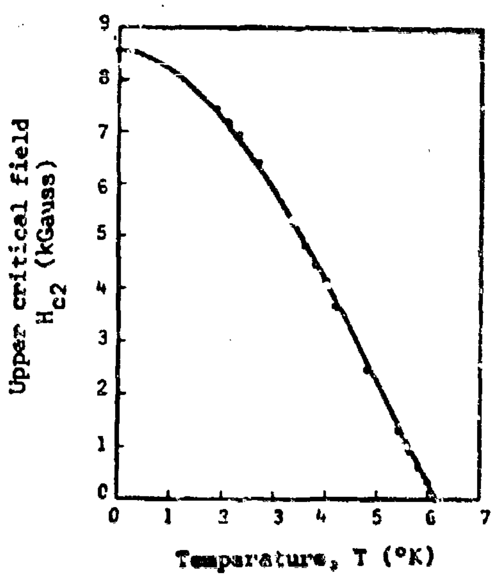
[Ref. 21845]

*H_{ps} Paramagnetic superconductivity onset field

† H_u Upper critical field

NIOBIUM-TANTALUM

CRITICAL FIELD



Upper critical field for $Nb_{.5}Ta_{.5}$ as a function of temperature. T_c = 6.15°K.

- ° from ρ_f graph, 8.6(kGauss)
- – theory
- • measured by resistivity method

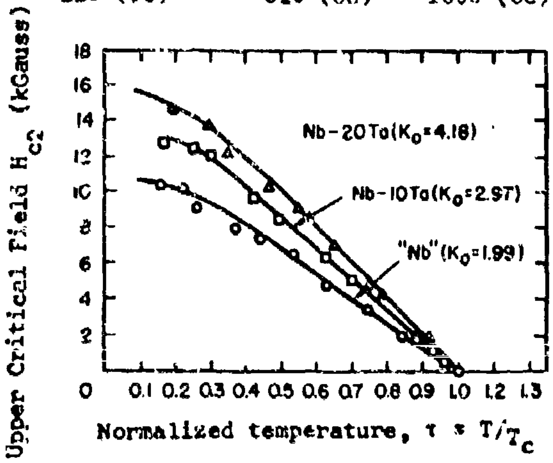
[Ref. 21841]

NIOBIUM-TANTALUM

CRITICAL FIELD

Transition Temperature and Critical Field

At.% Ta	Transistion temperature T_c (°K)	Critical Field Strength H_{c1}	H_c	H_{c2}	H_{c3}	Ref.
45	~6.5	-	-	-	-	21261
50	6.25	-	-	-	-	19477
"	-	-	-	3.55 (kGauss)	1.72 H_{c2}	13481
67	5.6	110 (Oe)	310 (Oe)	1600 (Oe)	-	14582



Upper critical field as a function of temperature for the following samples, as rolled.

$K_o = \chi_{e0} + \chi_{\ell 0}$, where χ_e is the intrinsic contribution to the order parameter and χ_ℓ is the impurity scattering contribution. The values are given for $\tau = 0$,

[Ref. 21259]

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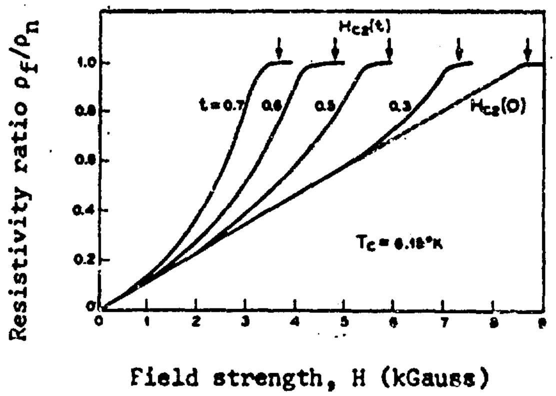
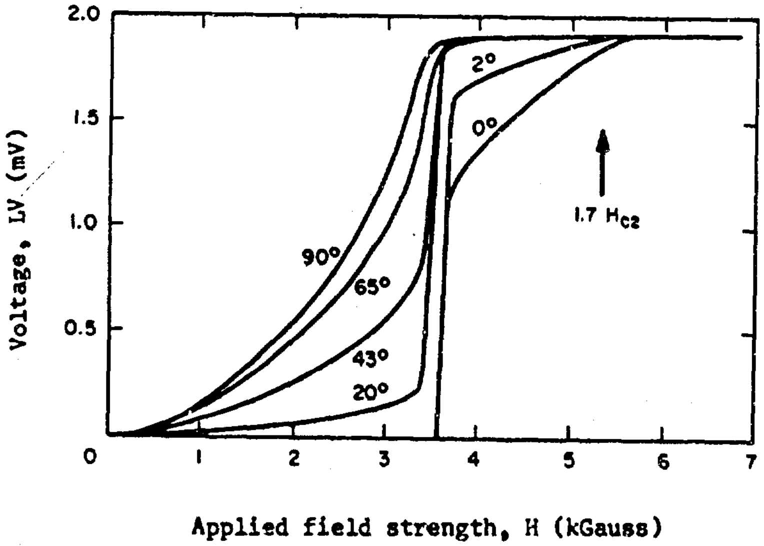
NIOBIUM-TANTALUM

CRITICAL FIELD

Ratio of flow resistivity to normal resistivity as a function of field strength H, for $Nb_{0.5}Ta_{0.5}$. The t values are the ratio T/T_c for $T_c = 6.15°K$. H_{c2} values are shown for each t and the dashed line indicates expected behavior at t = 0. $H_{c2}(0)$ = 8.6 (kGauss).



[Ref. 21841]



Resistive transitions in a $Nb_{.5}Ta_{.5}$ sheet 1.5 cm x 0.25 cm x 716 (10^{-3})cm. The data are take at T= 4.2°K, I = 500 mA and J = 260 amp/cm^2 and at different H to J orientations. H_{c2} = 3.55 kGauss and H_{c3} = 1.7 H_{c2}, theoretical. The sample was annealed.

[Ref. 13481]

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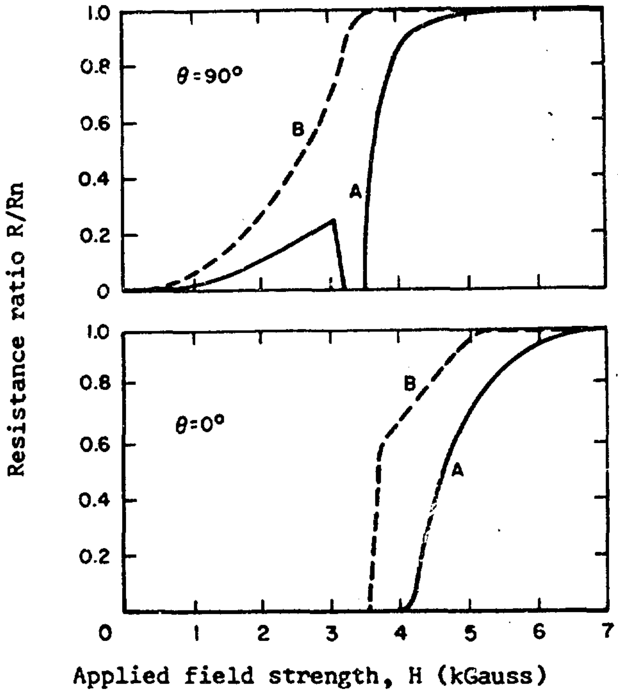
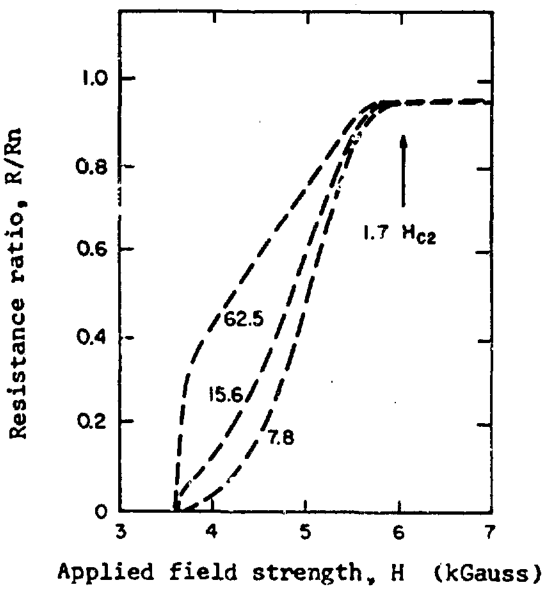
NIOBIUM-TANTALUM

CRITICAL FIELD

Resistive transitions reduced from voltage measurements, on a $Nb_{.5}Ta_{.5}$ sheet. Data taken at $T = 4.2°K$ and $J \doteq 200$ Amp/cm^2. The samples are identical except that (b) has been annealed.

[Ref. 13481]





Resistive transistions in a $Nb_{.5}Ta_{.5}$ sheet 1.5 x 0.25 x 7.6 x 10^{-3} cm. The data are taken at $T = 4.2°K$, $H \parallel J$ and different current strengths. The R/Rn values are obtained from reduction of the previous voltage data H_{c2} = 3.55 kGauss and H_{c3} = 1.7 H_{c2}. The sample was annealed.

[Ref. 13481]

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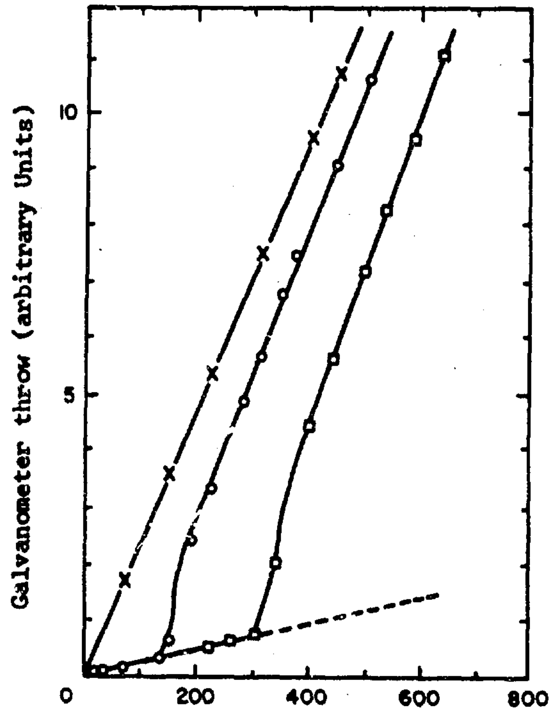
NIOBIUM-TANTALUM

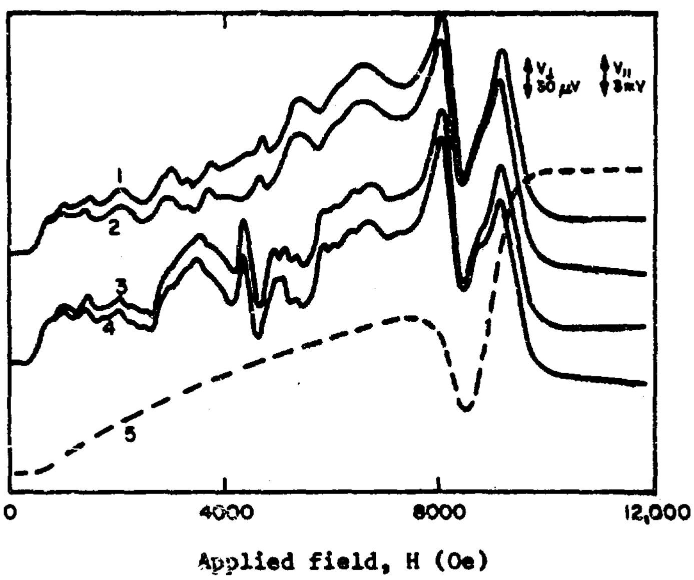
CRITICAL FIELD

Flux penetration curves for $Nb_{.64}Ta_{.36}$ alloy. Cylindrical rods, zone-refined.

□ T = 4.2°K
o T = 6.0°K
X T = 8.2°K

[Ref. 12452]





Transverse and longitudinal voltages as a function of magnetic field strength for $Nb_{.5}Ta_{.5}$ sample. The Hall voltage may be derived by substracting two corresponding curves. The polarity of the recorder was reversed in (2) and (3).

(1) H_-i_+
(2) H_+i_-
(3) H_-i_-
(4) H_+i_+

$\left.\right\}$ $V\perp$ (for 1–4)

(5) $V \parallel$

T = 1.3 °K
J = 3 x 10^3 amp/cm^2
J ∥ R.D.

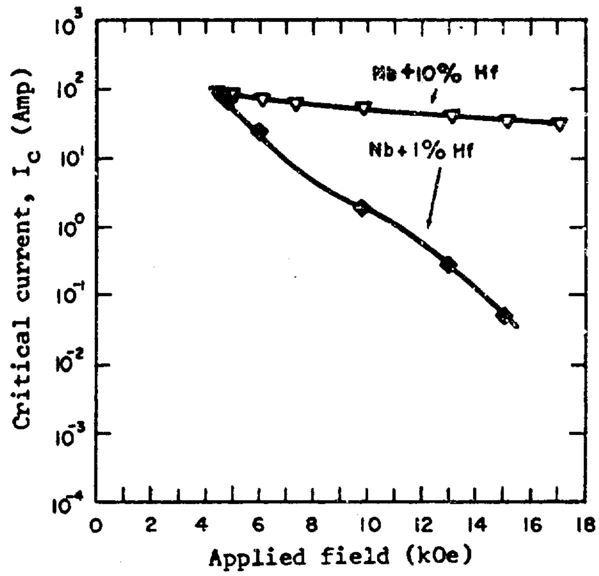
[Ref. 21260]

NIOBIUM-HAFNIUM

CURRENT DENSITY

Critical current for two niobium-hafnium wire (0.030 in. diam.). The values were taken in a transverse magnetic field on arc-melted samples.

[Ref. 10778]



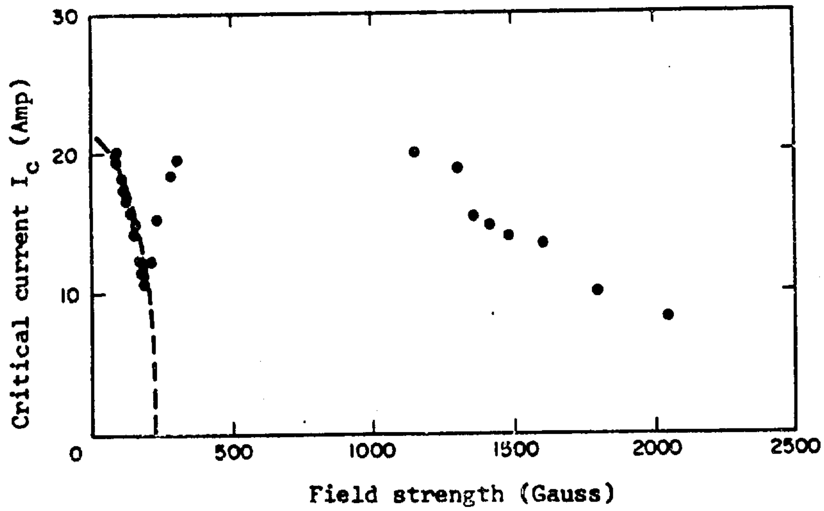
Critical Current Density

Symbol	Values (10^3 Amp/cm^2) Rolling plane H ∥	H ⊥	Unrolled	Samples	Temperature
J_c	2.6	0.08	0.08	25 at.% Hf alloy arc-melted and inverted 6 times.	4.2°K

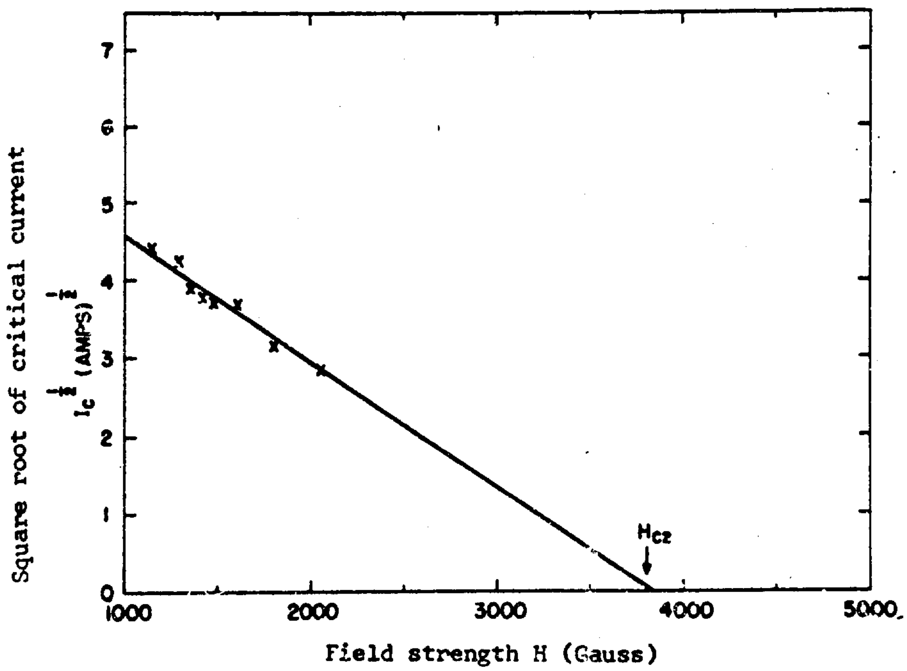
[Ref. 10713]

NIOBIUM-TANTALUM

CURRENT DENSITY



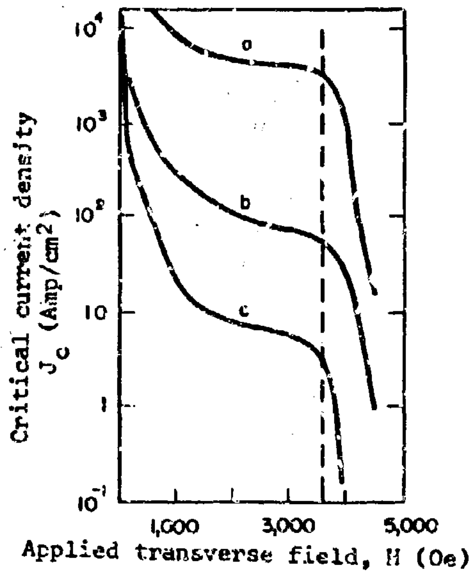
Critical current for $Nb_{55}Ta_{45}$ as a function of field.
[Ref. 21843]



Square root of critical current as a function of field for $Nb_{55}Ta_{45}$.
[Ref. 21843]

NIOBIUM-TANTALUM

CURRENT DENSITY



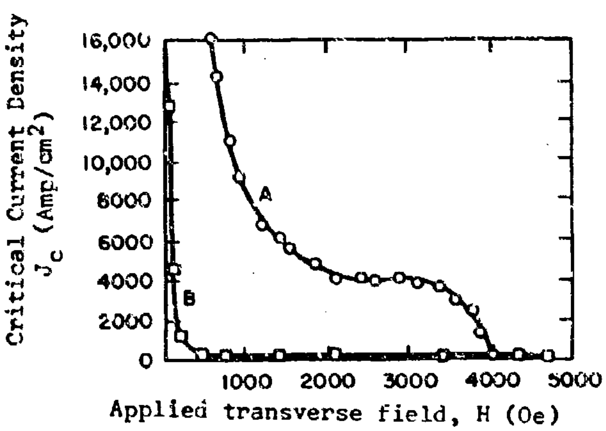
Critical current density for $Nb_{.55}Ta_{.45}$ wire swaged, drawn and annealed. The effect of annealing time is shown.

a) annealed 30 min, 1473°K, 10^{-4} - 10^{-5}mm Hg

b) annealed 24 hours, ~1800°K, ~$5x10^{-2}$mm Hg

c) annealed 48 hours, ~1800°K, ~$5x10^{-2}$mm Hg

[Ref. 21848]

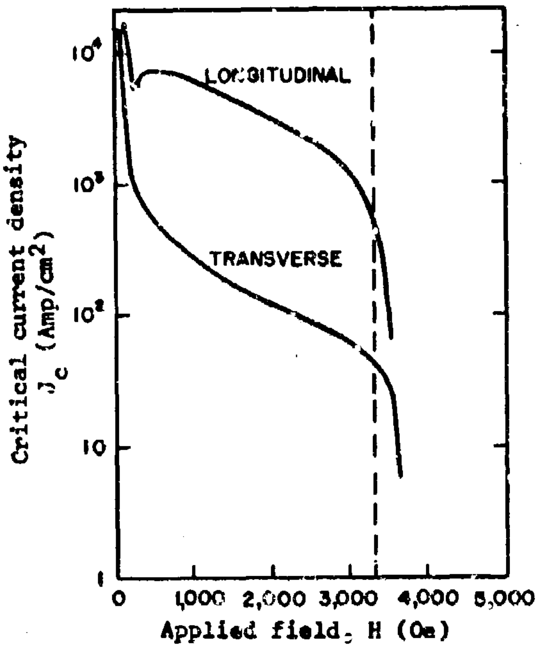


Critical current density ~~for~~ $Nb_{.55}Ta_{.45}$ alloy cold drawn wires (a) before annealing (b) after annealing for 25 hrs. hours at 5 x 10^{-8} Torr at about 1500°C. Data taken at 4.2°K.

[Ref. 21261]

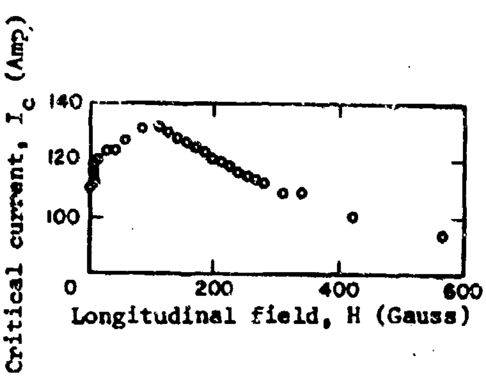
NIOBIUM-TANTALUM

CURRENT DENSITY



Critical current density for a $Nb_{.55}Ta_{.45}$ wire, annealed 24 hours. The data are shown for longitudinal and transverse fields.

[Ref. 21848]



Critical current for $Nb_{.50}Ta_{.50}$ wire, 0.125 cm diameter, annealed for 1 hour at 1100°C and 10^{-6} Torr, resistivity ratio $\approx$ 30. Data taken at 4.2°K with I|| H.

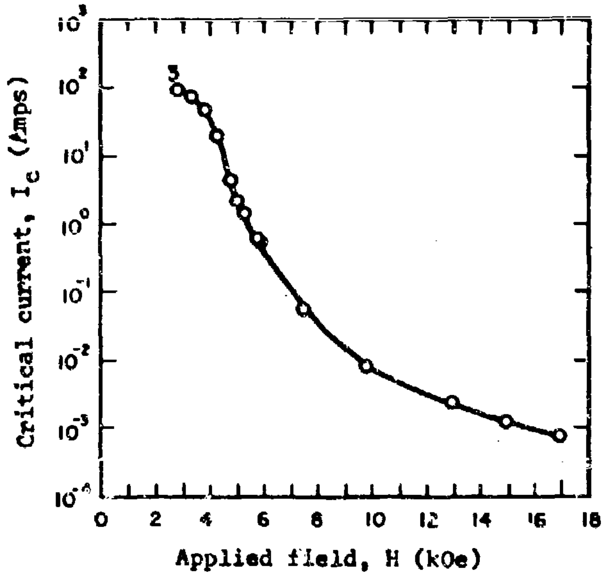
[Ref. 20904]

NIOBIUM-TUNGSTEN

CURRENT DENSITY

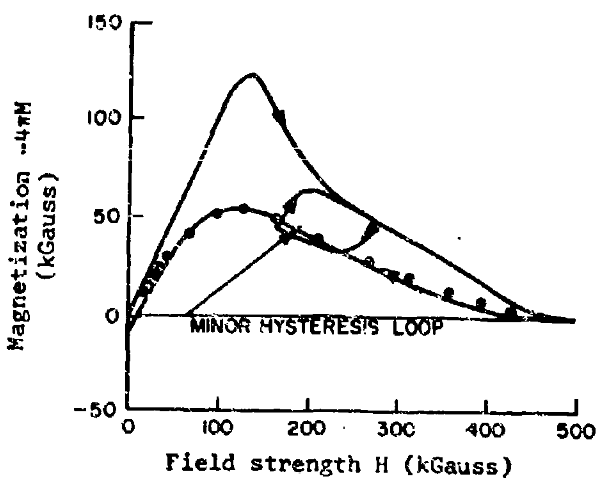
Critical current as a function of transverse field strength for a 1% tungsten, niobium-tungsten alloy.

[Ref. 10778]



NIOBIUM-TANTALUM

MAGNETIC HYSTERESIS



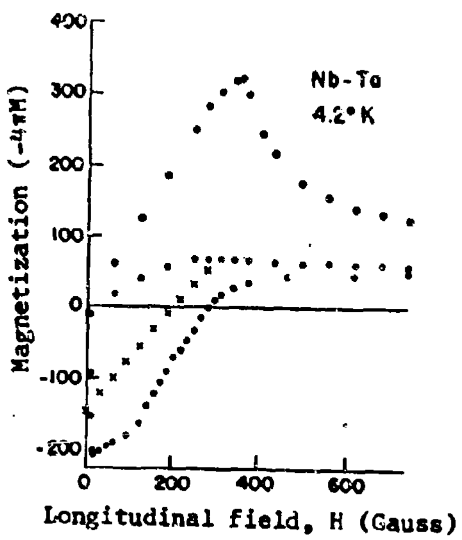
Magnetization for $Nb_{.95}Ta_{.05}$ wires in a longitudinal field. Data taken at 8.4°K.

• cooled in a fixed field

[Ref. 21843]

NIOBIUM-TANTALUM

MAGNETIC HYSTERESIS



Magnetization of $Nb_{.50}Ta_{.50}$ wire 0.125 cm diameter, annealed for 1 hour at 1100°C and 10^{-6} Torr, resistivity ratio ≈30. Data at 4.2°K.

- • Magnetization (I=0) H→
- o Flux expulsion (Meissner effect) upon cooling in longitudinal field
- x Magnetization after cooling at 0.32 kGauss H→
- • Paramagnetic magnetization at I_c. The sample is cooled through Tc in constant field.

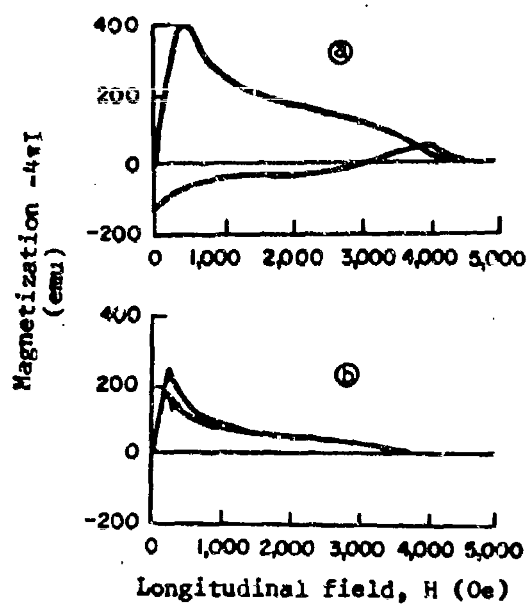
[Ref. 20904]

Magnetization of $Nb_{.55}Ta_{.45}$ wire, swaged, drawn and annealed. Data taken at 4.2°K.

a) one-stage annealed, 30 min. at 1473°K, 10^{-4} - 10^{-5}mm Hg vacuum.

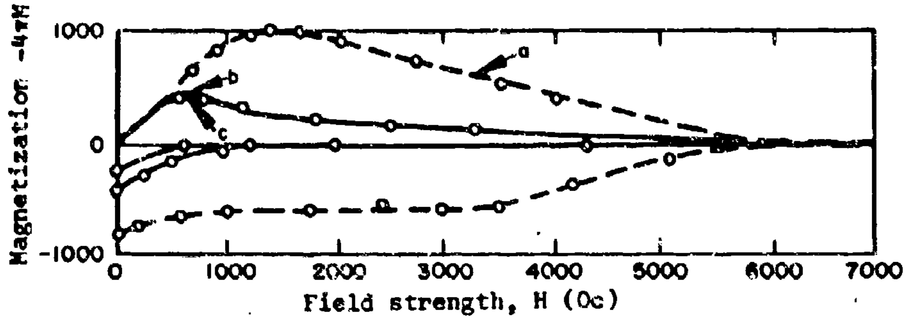
b) annealed 48 hours at ~1000°K in ~5×10^{-8}mm Hg vacuum.

[Ref. 21848]



NIOBIUM-TUNGSTEN

MAGNETIC HYSTERESIS



Magnetization as a function of field strength for a niobium-tungsten alloy (9.2 at .% W)

(a) heavily cold worked
(b) bulk rods (1.2 cm x 0.6 cm diam.)
(c) powders 45-60 μ-size particles

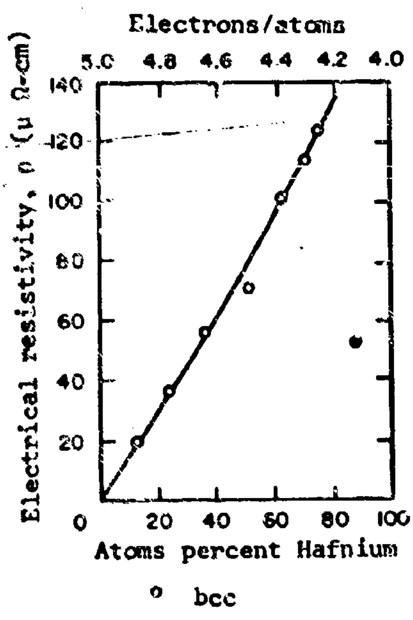
[Ref. 10778]

NIOBIUM-HAFNIUM

ELECTRICAL RESISTIVITY

Electrical resistivity for niobium-hafnium system as a function of the hafnium content, data taken at 1.2°K.

[Ref. 11924]



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NIOBIUM-HAFNIUM

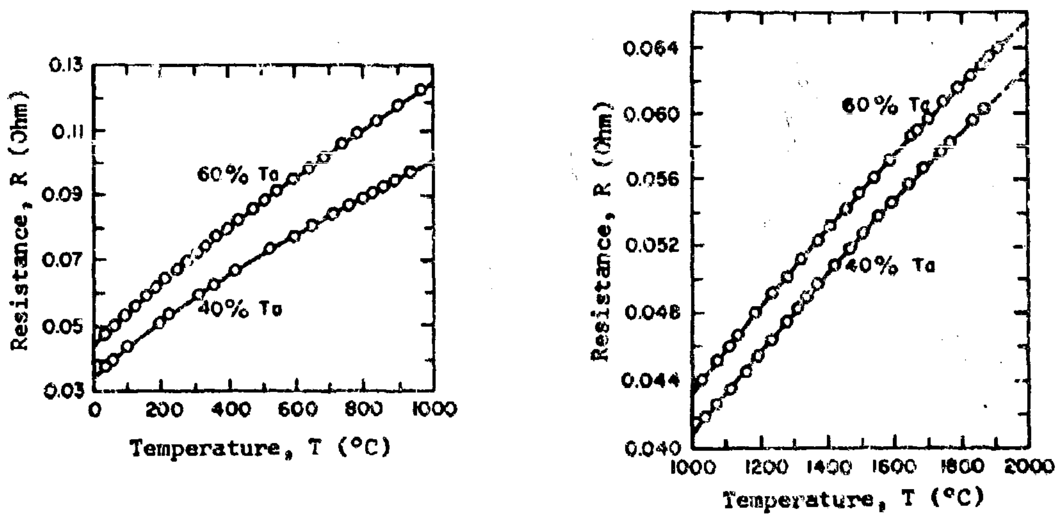
ELECTRICAL RESISTIVITY

Symbol	Values (μΩ-cm)	at. % Hf	Symmetry	Method
ρ	19.1	12.5	bcc	arc-melted
	36.3	25.0		
	57.2	37.5		
	68.0	50.0		
	100.3	62.5		
	114.4	70.0		
	124.4	75.0		
	53.2	87.5	hcp + bcc	

[Ref. 11924]

NIOBIUM-TANTALUM

ELECTRICAL RESISTIVITY



Resistance for $Nb_{60}Ta_{40}$ and $Nb_{40}Ta_{60}$ alloys from 0-2000°C

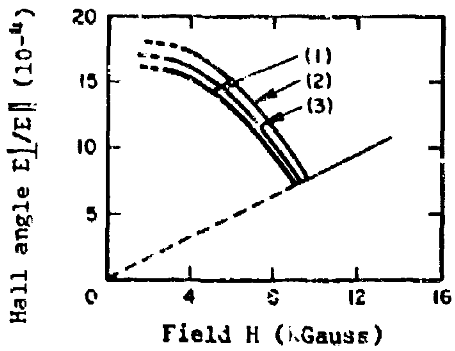
[Ref. 21252]

NIOBIUM-TANTALUM

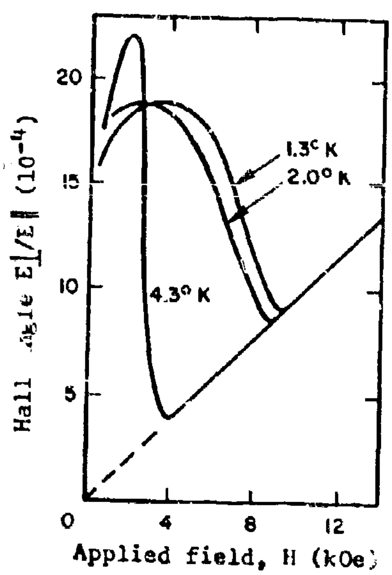
HALL ANGLE

The Hall angle for $Nb_{.50}Ta_{.50}$ as a function of magnetic field strength. Data taken at 1.3°K.

1) annealed
2) etched
3) cold-rolled



[Ref. 20825]



Hall angle as a function of field for $Nb_{.5}Ta_{.5}$ alloy, cold rolled sheets 22 μ thick.

[Ref. 21260]

SECTION 6
NIOBIUM-RHENIUM &
NIOBIUM-OSMIUM SYSTEMS

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NIOBIUM ALLOYS AND COMPOUNDS

NIOBIUM-RHENIUM AND NIOBIUM-OSMIUM SYSTEMS

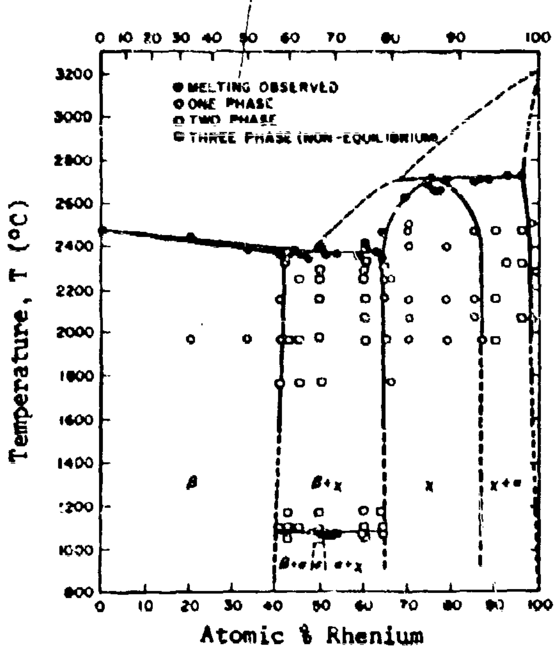
GENERAL

Nb-Re The niobium rhenium system forms two distinct compounds, β in the niobium-rich region and χ in the rhenium-rich region. Except for a few values given in the mixed β+χ region most of the transition temperatures are reported in the χ rhenium-rich region of the system.

Nb-Os The niobium-osmium system forms three primary crystallographic structures, α-Mn, σ, and β-tungsten [Ref. 17299]. This latter structure gives the lowest T_c of the three crystalline forms, 1.05°K [Ref. 20332] while the α-Mn gives the highest T_c, 2.52°K [Ref. 17299].

NIOBIUM-RHENIUM

GENERAL



Proposed phase diagram for niobium-rhenium system.

[Ref. 21231]

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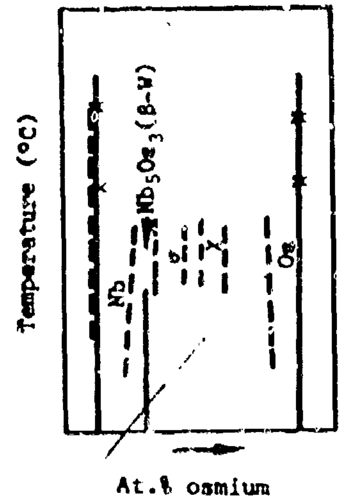
NIOBIUM-OSMIUM

GENERAL

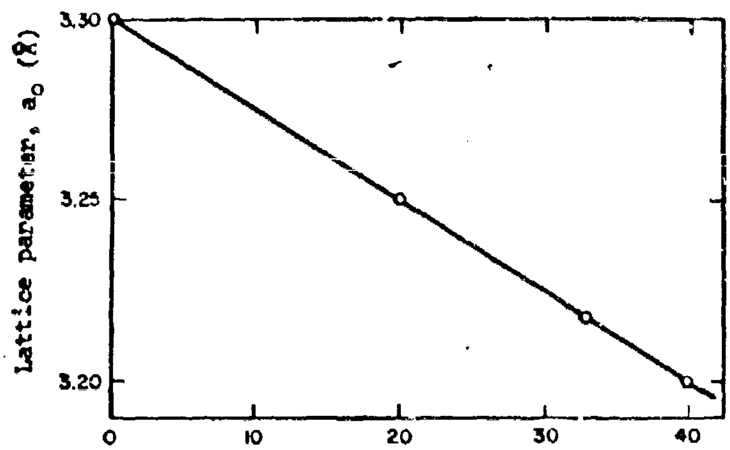


Appearance of different phases in the niobium-osmium system. Sigma phase exists from 30-54%, Os and chi phase from 55-65% Os.

[Ref. 20718]

NIOBIUM-RHENIUM

GENERAL

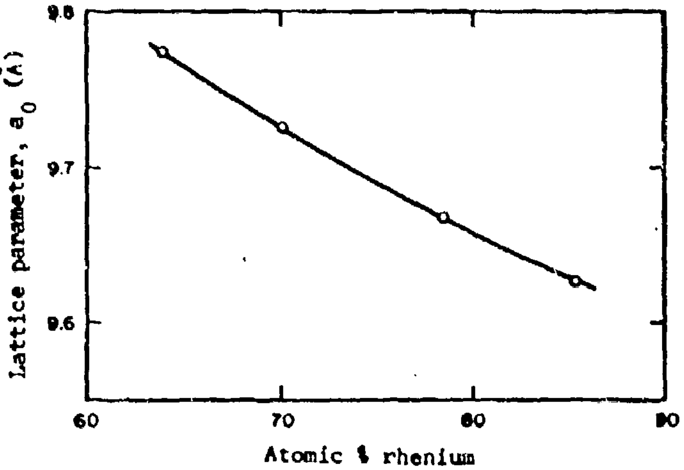


Lattice parameter for bcc niobium-rhenium system.

[Ref. 21231]

NIOBIUM-RHENIUM

GENERAL



Lattice parameter for α-Mn, niobium-rhenium system.

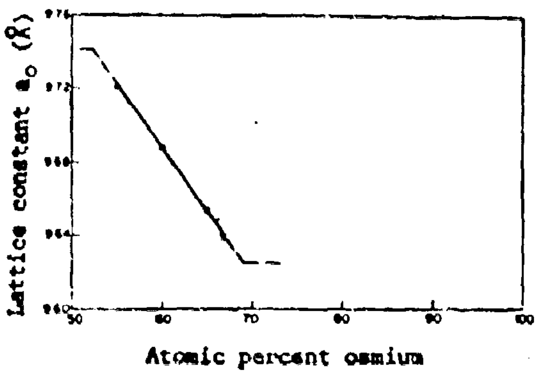
[Ref. 21231]

NIOBIUM-OSMIUM

GENERAL

Lattice constant for α-Mn Nb-Os system.

[Ref. 21851]



NIOBIUM-RHENIUM

TRANSITON TEMPERATURE

Lattice Constant and Transition Temperature

At. % Re	Lattice constant Å a_o	c_o	Transition Temperature T_c(°K)	ΔT†	Symmetry	Notes	Ref.
~20	-	-	4.8	-	Nb, bcc	Composition given as $Nb_{44}Re$	10784
25*	3.228	-	-	-	"	As melted, annealed 1000°C, 7 days.	20625
50	3.194	-	-	-	"	As melted.	20625
"	9.783	5.115	-	-	σ-tetr	"	20625
"	9.79	5.10	3.8-2.0	-	"	Cooled from 1250°C.	9686
60	9.781	-	2.36	0.2	α-Mn	Cooled from 1250°C.	9686
	-	-	2.0	-	"	-	7648
	9.773	-	-	-	"	Cooled from melting point, 6.2 electrons/atom.	9686
	9.77	5.14	2.5	0.2	σ-tetr	"	9686
62	-	-	2.45	-	α-Mn	6.24 electrons/atom.	15323
82	-	-	8.89	-	"	-	7648

†ΔT is the width of the transition region

* Nb_3Re, Cu_3Au type, ao = 4.207 Å, sample preparation HCl transport method [Ref. 21843]

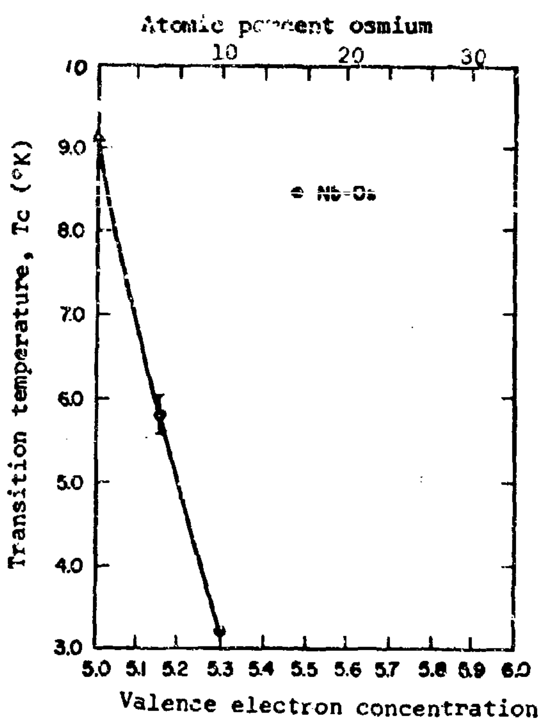
NIOBIUM-OSMIUM

TRANSITION TEMPERATURE

Lattice Constant and Transition Temperature

At.% Os	Symmetry	Lattice Constant (Å) a_o	c_o	Transition temperature T_c (°K)	Electrons/atom	Notes	Ref.
25*	β-tungsten	-	-	1.05	5.8	-	9620
"	"	5.1359	-	< 1.7	"	Standard sample preparation.	18750
40	σ tetragonal	9.858	5.066	-	6.2	Arc-melted in a gettered argon atmosphere.	20625
"	tetragonal	9.844	5.056	1.78	"	-	17299
50	α manganese	9.778	-	-	6.5	Arc-melted in a gettered argon atmosphere.	
67	"	-	-	2.[illegible]2	7.0		17299

* Nb_3Os, Cu_3Au type, a_o = 4.207 Å, sample prepared by HCl transport method [Ref. 21843]

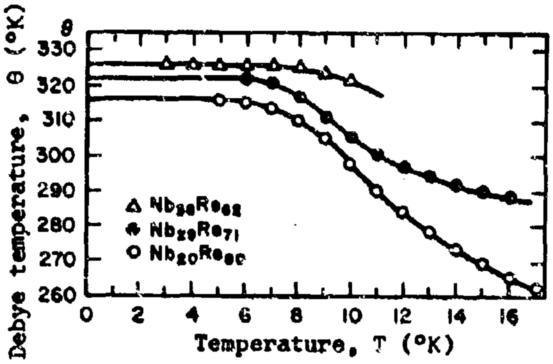


Transition temperature for niobium-osmium system.

[Ref. 14468]

NIOBIUM-RHENIUM

DEBYE TEMPERATURE



Debye temperature for three niobium-rhenium alloys with A 12-type crystal structure.

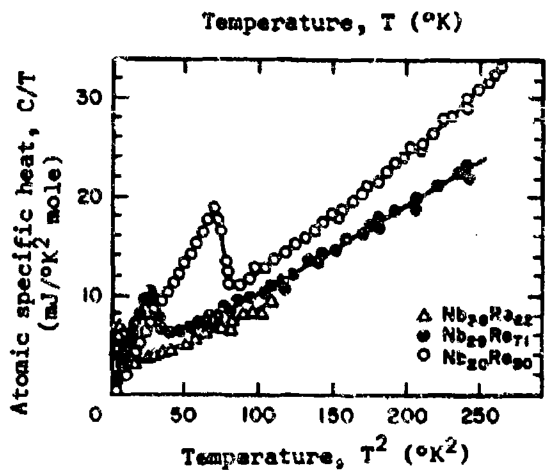
[Ref. 14464]

NIOBIUM-RHENIUM

SPECIFIC HEAT

Atomic specific heat for these niobium-rhenium alloys with A 12-type crystal structure.

[Ref. 14464]



NIOBIUM-RHENIUM

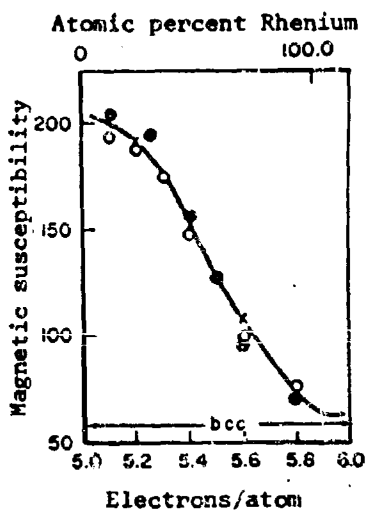
SPECIFIC HEAT

Thermal Properties

Formula	Coefficient of Electronic Specific Heat. γ (10^{-4} cal/°K^2 mole)	Debye Temperature θ (°K)	$\frac{N(0)V}{\gamma}$ (cal/°K^2 mole)$^{-1}$	Ref.
$Nb_{.38}Re_{.62}$	6.4	300 ± 10	340	15323

NIOBIUM-RHENIUM

MAGNETIC SUSCEPTIBILITY



Susceptibility of niobium-rhenium system. Data are given for Nb-Tc and Nb-Mo for comparison.

• Nb-Re

x Nb-Tc

o Nb-Mo

[Ref. 19617]

NIOBIUM-RHENIUM AND NIOBIUM-OSMIUM

MAGNETIC SUSCEPTIBILITY

Formula	χ (10^{-6} cm^3/g)	χ at (10^{-6} cm^3/g	χ (10^{-6})*	Symmetry	Notes
$Nb_{.50}Re_{.50}$	61	8500	880	α-Mn	Cooled from 1250°C.
$Nb_{.40}Re_{.60}$	66	9800	1000	σ	Cooled from ∿2400°C.
$Nb_{.60}Os_{.40}$	74	"	990	"	"
$Nb_{.50}Os_{.50}$	60	8500	890	α-Mn	"

* Volume susceptibility, 300°K.

[Ref. 9686]

SECTION 6
NIOBIUM IRIDIUM & NIOBIUM PLATINUM SYSTEMS

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. NIOBIUM ALLOYS AND COMPOUNDS

NIOBIUM-IRIDIUM AND NIOBIUM-PLATINUM SYSTEMS

LATTICE CONSTANT AND TRANSITION TEMPERATURE

Nb-Ir

At.% Ir	Formula	Symmetry	Lattice Constant Value (Å) a_o	c_o	Transition temperature °K	Notes	Ref.
15	Nb + Ir	bcc	3.262	-	-	as melted	20625
25	Nb_3Ir	β-tungsten	-	-	1.7	-	9625
"	"	"	5.139	-	-	as melted	20625
37	-	σ tetr.	-	-	7.9	-	7648
"	-	"	9.86	5.06	2.4 midpoint	-	9686
			-	-	0.1 width	-	"
40	Nb_3Ir_2		9.834	5.052	9.8	-	17299
50	-	fcc	3.895	-	-	annealed	20625
75	$NbIr_3$	"	3.893	-	-	3 days 1200°C	20331

Nb-Pt

At.% Pt	Symmetry	Lattice constant (Å) a_o	b_o	c_o	Transition temperature T_c (°K)	Notes	Ref.
25*	β-tungsten	5.153±.003	-	-	9.2	-	20332
37.5	σ-tetr	9.91	-	5.12	3.73	-	17299
"	"	-	-	-	4.2	-	15323
38.0	"	9.91	-	5.13	4.01	annealed & quenched	9686
52.0	orthorhombic	2.780	4.983	4.611	-	-	20357
75.0	"	5.534	4.873	4.564	-	-	"
"	monoclinic	5.537	4.870	27.33	-	-	"

* Nb_3Pt, Cu_3Au type, a_o = 4.207 Å, sample prepared by HCl transport method[Ref. 21843]

NIOBIUM-PLATINUM

THERMAL PROPERTIES

Formula	Coefficient of Electronic Specific Heat $\gamma \times 10^{-4}$ (10^{-4}cal/mole °K^2)	Debye Temperature θ (°K)	$\frac{N(\epsilon)V}{\gamma}$ (cal/mole °K^2)$^{-1}$	Ref.
$Nb_{.625}Pt_{.375}$	9.1 ± 0.2	335 ± 10	.260	15323

γ, θ, and T_c from preceding table were all taken on one sample.

NIOBIUM-PLATINUM

MAGNETIC SUSCEPTIBILITY

System	χ_{tot}* (10^{-6} emu/g. at)	χ_{add} (10^{-6} emu/g. at)	χ (10^{-6} cm^3/g	χ_{at} (10^{-6} cm^3/g	χ (10^{-6})**	Crystal-lography
$Nb_{.62}Pt_{.38}$†	67	40	51	6700	660	σ

* $\chi_{tot} = \chi_{ion} + \chi_{Pauli} + \chi_{L.P.} + \chi_{add}$ [Ref. 14464]

$\chi_{L.P.}$ (Landau-Peierls) electronic specific heat contribution.

† $Nb_{.62}Pt_{.38}$ cooled from 1300°K. [Ref. 9686]

** Volume susceptibility, 300°K.

SECTION 6
NIOBIUM-GOLD SYSTEM

NIOBIUM ALLOYS AND COMPOUNDS

NIOBIUM-GOLD SYSTEM

GENERAL

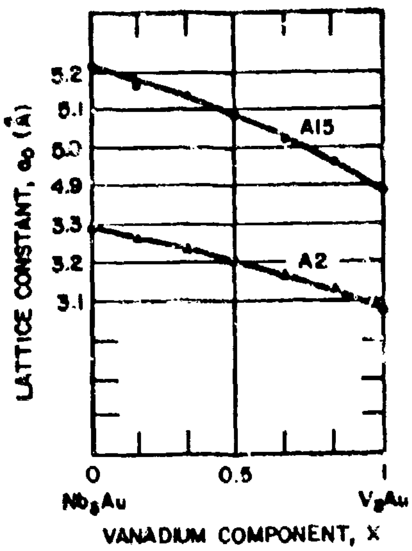
Nb-Au Of the four niobium-gold compounds only the Nb Au shows a transition temperature. This compound takes on the β-tungsten structure primarily; however, by quenching carefully an A 2 structure is formed which shows a much lower T_c.

Niobium-Gold Crystalline Phases

Compound	Structure	Crystal
Nb_3Au	Cubic	A 15 (β-W)
Nb_3Au	Cubic	A 2
Nb_3Au_2	Tetragonal	D^{17}_{4h} I4/mmm
$Nb_{11}Au_9$	Cubic	β-Mn
$NbAu_2$	Hexagonal	AlB_2

NIOBIUM-GOLD

GENERAL



Lattice constant of $(Nb_{1-x}V_x)_3$ Au as a function of composition.

• A 15 crystal structure, annealed

▲ A 2 crystal structure, quenched

[Ref. 15189]

Both binary compounds Nb_3Au and V_3Au, as well as the ternary Nb_3Au-V_3Au, form into the A 15 structure when prepared and left "as cast". Bucher et al [Ref. 15189] were able to convert this A 15 sample to an A 2 type structure with a quenching method of blowing cold argon onto the melt immediately after interrupting the primary current. The return of these A 2 samples to A 15 structure was accomplished by annealing:

Nb_3Au	20 hrs at 105[illegible]°C
"	1/2 hr at [illegible]00°C
Nb_3Au-V_3Au	27 hrs at 850°C
V_3Au	8 hrs at 760°C

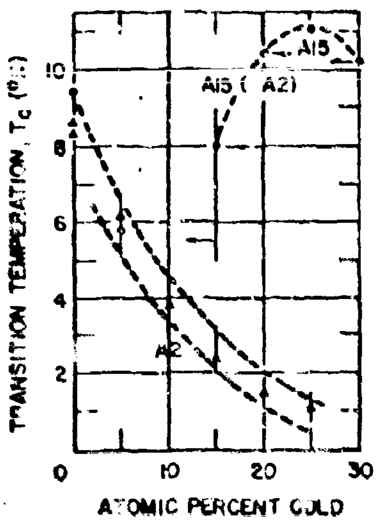
NIOBIUM-GOLD

TRANSITION TEMPERATURE

Lattice Constants and Transition Temperature

At.%Au	Formula	Lattice constants (Å) a_o	c_o	Transition Temperature T_c (°K)	Symmetry	Ref.
25*	Nb_3Au	5.21± .001	-	-	β-tungsten(A 15)	20025
		-	-	10.6		15608
		-	-	11.5		9620
		-	-	11.0		15189
		3.29	-	1.2	A 2	"
40	Nb_3Au_2	3.38	5 x 3.04	.	D_{4h}^{17} $I4/mmm$	20226
45	$Nb_{11}Au_9$	7.05	-	-	β-Manganese	"
67	$NbAu_2$	4.61	2.72	-	AlB_2	"

* Nb_3Au, Cu_3Au type, a_o = 4.207 Å, sample prepared by HCl transport method [Ref. 21843]



Transition temperature of niobium-gold system as a function of atomic percent gold. Below 25 at.% gold there are traces of A 2 structure present in the A 15 structure.

o A 15 crystal structure, annealed

Δ A 2 crystal structure, quenched

[Ref. 15189]

SECTION 6
NIOBIUM-BISMUTH SYSTEM

NIOBIUM-BISMUTH

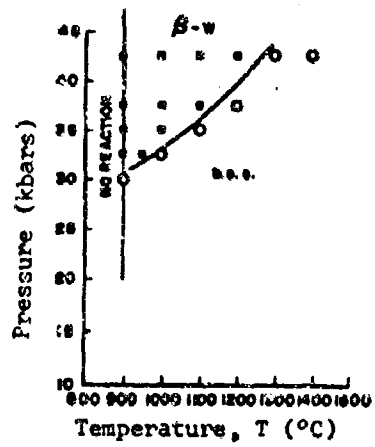
GENERAL

Pressure-temperature phase diagram for Nb_3Bi.

□ β-tungsten

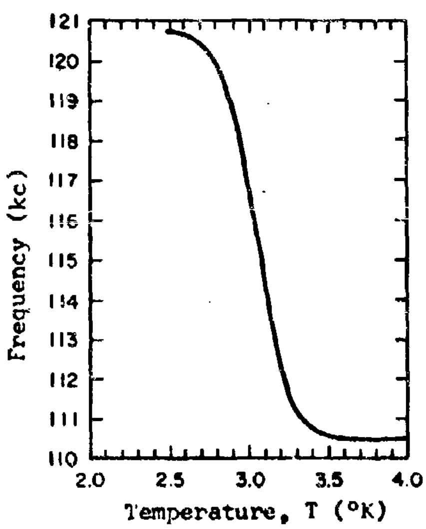
o bcc

[Ref. 17303]



NIOBIUM-BISMUTH

TRANSITION TEMPERATURE



Transition temperature for bcc Nb_3Bi, measured by the Schawlow and Devlin susceptibility technique. The circuitry of this experiment is such that the transition curve shows a higher frequency at the lower temperatures.*

* Private communication with D.H. Killpatric now with Douglas Aircraft Co. Santa Monica California.

[Ref. 17303]

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S-7 Glossary of Electronic Properties. Emil Schafer. January 1965. 86 p. (AD-616 783)

EPIC Bulletin. v. 1, no. 1, January 1965-. A monthly two-page news sheet containing items of interest to many of our users.

Electrical and Electronic Properties of Materials. Information Retrieval Program. Technical Documentary Report No. ASD-TDR-62-539, June 1962, Final Report (Covers work from July 5, 1961 - June 15, 1962. H.T. Johnson, E. Schafer and E.M. Wallace, 219 p. (AD-289 546)

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The Electronic Properties Information Center, Technical Report AFML-TR-65-68. March 1965, H.T. Johnson and D.L. Grigsby (Covers work from February 1, 1965 - January 31, 1965), 80 p. (AD-466 104)

(The four previous reports, ASD-TDR-62-539, Part I, II, and III, and AFML-TR-65-68, are progress reports that describe the establishment, purpose, operation, programs and accomplishments of EPIC.)

Electronic Properties of Materials; A Guide to the Literature. Edited by H.T. Johnson. 2 v. New York, Plenum Press, 1965. 2000 p. $150.00.

Interim Reports

1. Selected Electret Bibliography. August 1965. 58 p.
2. Electrical Conductivity and Resistivity of Selected Metals and Alloys. No Date. 16 p.
3. Electrical and Magnetic Properties of the 300 Series Stainless Steel. July 19, 1965. 12 p.
4. Compilation of Information on High Electrical Conductivity Copper Alloys. August 17, 1965. 49 p.
5. Behavior of Dielectric Materials and Electrical Conductors at Cryogenic Temperatures. (A Bibliography.) August, 1965. 87 p.
6. A Bibliography of Superconductor Devices and Materials. August, 1965. 1 p.
7. A Compilation of References on Charged Transfer Complexes and Compounds. August, 1965. 18 p.
8. A Bibliography of Holdings on Thermoelectric Properties of Copper, Gold, Silver, and Their Alloys. August 2, 1965. 13 p.
9. A Bibliography of Holdings on Thermomagnetic Properties of Selected Metals. August, 1965. 33 p.
10. A Bibliography on High Temperature Dielectric Materials. November, 1965. 10 p.
11. A Bibliography of RFI and Electromagnetic Shielding (including Shielded Rooms). October 11, 1965. 3 p.
12. A Bibliography of High Temperatures Electrical Conductor References. November, 1965. 4 p.
13. A Bibliography on Encapsulation, Embedment, and Potting Compounds. December 22, 1965. 9 p.
14. A Reference List on Titanium Oxide Dielectric Films. January 11, 1966. 1 p.
15. A List of Ultra High Frequency References Containing Materials/Property Data. January, 1966. 3 p.
16. A Compilation on Silver-Cadmium and Nickel-Cadmium Batteries. January, 1966. 60 p.
17. A Selected Bibliography and Data on Boron Nitride. January 1966. 60 p.
18. A Bibliography on Tantalum Metal Films for Electric Applications and Related Information. January, 1966. 6 p.

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